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Note that the times shown in the study plan overleaf do not include the time that you will need to answer the questions on the DVD and the TMA, watching the television programme, making use of the set book, attending sessions at your local or regional centre or reflecting on what you have learned and how you have learned it. Past students have also commented that *our* estimates of the times needed for the study of the DVD-multimedia activities are likely to be low.

Study Guide for Block 7

The quantum world marks the half-way point of the course, and is the final destination on our quest of 'taking the world apart'. In this block we make a relatively short journey, from the world of atoms that you learned about in Block 6 down to the subatomic world and the fundamental constituents of everything around us.

In Sections 1–3, the distinctive features of atomic and subatomic structures that comprise the quantum world are described. You will see that atoms exist only in states of certain characteristic energy, but that within these states the positions and motion of the electrons are intrinsically uncertain. Be prepared to explore some ideas here that may be quite at odds with anything you have encountered before!

Sections 4, 5 and 6 look in turn at the constituents of atoms, the constituents of nuclei, and finally the fundamental particles that make up the quantum world. As shown in the study plan overleaf, each of these sections has a DVD-multimedia activity. These activities contain material that is not presented elsewhere in the block; consequently, you will benefit most if you can study them at the point that they are introduced in the book.

Sections 7, 8 and 9 then switch emphasis and concentrate on light and other electromagnetic radiation. They include two DVD-video activities, the first of which provides essential information regarding the practical work that you will carry out in Section 10. The second DVD-video activity shows an experiment being carried out and provides advice on how to take measurements, record experimental data and deal with experimental uncertainties. This too will provide useful information for the practical work in Section 10, and also about experiments in general, such as those you will encounter if you attend the SXR103 residential school. Although it is best to study the two DVD-video activities at the times indicated in the book, you can delay doing so until more convenient times if necessary. However, you should certainly watch both of them before tackling the practical work in Section 10.

Section 10 includes the most extensive piece of practical work in the course so far. This practical work is vital. Without it, you will miss out on your chance to explore a central theme: how measurements of light from atoms help us to understand atomic structure. Activity 10.1 will probably take you at least two hours to complete, so it is worthwhile deciding now when you can set aside some time to do it. Also you should look in the Study File at the list of non-kit items you will need to provide, so that you can collect them together in advance of the activity. If you are short of some items, you may well be able to improvise with something else that works just as well. Ingenuity is the key here! However, note particularly that you will need an angle-poise lamp or a table lamp, an energy saver light bulb (see Box 10.1.1, *Energy saver bulbs* in the Study File) and the diffraction grating from the practical kit.

The study plan overleaf shows how you might divide your time over the two weeks allocated to Block 7. You will also need to set aside time for the other components mentioned below.

As with earlier blocks, the Block 7 DVD includes a set of questions to help you assess your understanding of this block. These ten questions may be studied in batches after you have completed Sections 1–3, Sections 4–6, and Sections 7–10, or as revision after you have completed the whole block. The DVD also includes an introduction to the S103 graph plotting computer software, which you may find useful during your study of this and later blocks.

Assessment of Block 7 is in two parts. Sections 1–6 are assessed in TMA 06 and Sections 7–11 are assessed in TMA 09. If you are not intending to submit TMA 09 then you may choose to spend less time on Sections 7–11; however, you should ensure that you read and understand the mathematics taught in Block 7 (Boxes 8.1, 8.2 and 8.3) and Block 11 (Boxes 2.2, 5.1 and 7.1) as these underpin, to a greater or lesser extent, concepts that you will need to rely on during higher level study.

One of the TV programmes 'Uncertain principles' relates directly to Block 7 Sections 1-6. The broadcast time can be found in the *Study Calendar*.

You should start your study of Block 7 by reading Section 1 of the book.

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4.1 DS

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7 The quantum world

All study times are in hours

Week	Sections of Book 7	Total study time	DVD-multimedia, and practical activities	DVD-video
1	**1** Introduction	$\frac{1}{2}$		
	2 Quantized energy	3		
	3 Quantum indeterminacy	3		
	4 Atomic structure	$1\frac{1}{2}$	multimedia	$\frac{1}{2}$
2	**5** Nuclear structure	$2\frac{1}{2}$	multimedia	$1\frac{1}{2}$
	6 Fundamental particles	$1\frac{1}{2}$	multimedia	$\frac{1}{2}$
	7 Understanding light	$\frac{3}{4}$		
	8 Light as a wave	$2\frac{3}{4}$	video	$\frac{3}{4}$
	9 Light as particles	$1\frac{3}{4}$	video	$\frac{3}{4}$
	10 Wave–particle duality	$2\frac{1}{2}$		2
	11 The world taken apart	$\frac{1}{4}$		
	'Uncertain principles' should be viewed at some time during or immediately after Section 6.			

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Study File for Block 7

Contents

Notes on activities	**1**
Comments on activities	**31**
Further reading	**42**
Objectives for Block 7	**43**
Appendix: what to do if you are short of time	**46**

Notes on activities

You should read through the notes for each activity before attempting it. After completing an activity you should study the relevant comments in the next section of the Study File.

No estimate of time is given for activities which should take 10 minutes or less.

Activity 2.1 Reflections on quantum ideas

In Section 2, you have met several ideas that seem to go against common sense — they conflict with your experience of how things behave in the world around you. You may have found these ideas difficult to come to terms with, and you are probably still unhappy about some of them. There are other ideas like this in Section 3, and thinking about these new ideas gives you an opportunity to test some of the techniques that you used in Block 6 for dealing with difficult concepts.

Pause for a moment to reflect on ideas that have been overturned so far in Block 7. In particular, think about the following questions.

(a) What did you think light was before you started studying Block 7? What do you think now? How have your ideas changed?

(b) On the basis of what you learned in Blocks 2 and 5, you probably thought of atoms as little billiard balls zooming around with kinetic energy (determined by mass and speed) that could take any value. In Block 7 you have discovered that the internal energy of atoms can only have certain values. What evidence has been given for this?

(c) Finally, think back to Section 14 of Block 6 where we introduced a model of an atom. Do you have a mental picture of the structure of an atom? How do you think that the protons, neutrons and electrons are arranged? Draw a sketch of your mental picture. Note that this is not a question with right or wrong answers — what is important is that you record the way in which *you* visualize an atom *now*.

Read the comments on (a)–(c) before starting Section 3.

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5.1 DS

SUP 82833 8

At the end of Section 3

(d) Now is the time to think again about the mental picture of the structure of an atom that you had before studying Section 3; we asked you to think about this and to draw a sketch of your mental picture in part (c) of this activity. Don't pass judgement yet as to whether that picture is right or wrong, but compare your picture with:

- the Rutherford model of the atom;
- the Bohr model of the atom;
- the Schrödinger model of the atom.

Now for each of these models write a sentence that describes the position of the electrons relative to the nucleus. Which one of the three models was your model most like?

(e) Section 3 has introduced you to ideas of quantum indeterminacy. Write a sentence explaining the meaning of the term 'quantum indeterminacy'. Which of the three models best illustrates this concept?

Activity 3.1 Quantum states

Familiarity with the notation for different quantum states and the numbers of quantum states for particular values of n and l will be important in Block 8 when we explore the underlying reasons for the periodicity of the Periodic Table and for chemical bonding between atoms. This activity will help you to consolidate your understanding of this notation by completing Table 3.1.1 so that it summarizes some of the important information.

(a) First, enter in the appropriate cells in Table 3.1.1 the notation for the quantum states of hydrogen that correspond to the allowed combination of quantum numbers with n between 1 and 5 and with l between 0 and 4.

(b) Then enter in the table the values for the energy levels E_n in the hydrogen atom.

(c) Finally, enter the total number of quantum states corresponding to each energy level in the right-hand column of the table, and enter the number of states corresponding to each particular value of the l quantum number in the final row of the table.

Table 3.1.1 Quantum states of hydrogen.

n	l					E_n/eV	Total number of states
	0	1	2	3	4		
1							
2							
3							
4							
5							
Number of states for each l							

Activity 3.2 Testing your strategies

(a) Look back at your responses to the different parts of Activity 2.1. In that activity you thought about models that you have used to help with some of the difficult concepts introduced in Sections 2 and 3. Make a list of the study techniques that you used when thinking about these models in Activity 2.1. Which of these techniques did you, personally, find most helpful?

(b) Now compare this list of study techniques with your notes from Block 6 Activity 15.1. In that activity, you compiled a list of techniques for dealing with difficult concepts. Have you used the techniques you thought of in Block 6 to help you to understand the concepts in Block 7?

Are there any techniques which you have used in Block 7 but which were not on your Block 6 list? These may need to be added to your general 'tool kit' of techniques that you use to help you to understand difficult material.

Were there any techniques which you thought of in Block 6 but have not used so far in Block 7? Would any of these have been helpful? There may be some which were just not appropriate on this occasion, but you should keep them in your tool kit — there may be other occasions when they will be useful. Similarly, if you think of any other new strategies as you work through the rest of the course, add them to your list. It would also be worth discussing the ways in which you cope with difficult concepts with students at your study centre, with your tutor, and perhaps also with students at residential school.

(c) Now think of a technique which you used in Block 6 to help you get to grips with a difficult concept, and which you have used again this block. Was it easier to use this technique here? Was it successful? Did you have to modify it to make it useful for the new situation?

Activity 4.1 Electrons in atoms

(*The estimated time for this activity is 30 minutes.*)

The aim of this activity is to reinforce your understanding of some of the important concepts of quantum physics that you met in Sections 2 and 3, particularly the relationship between energy levels, quantum states and electron clouds, and the relationships between energy levels and spectra. You will initially explore these relationships by investigating the hydrogen atom, and you will then discover the differences between the energy levels, electron clouds and spectra of hydrogen atoms, and those of singly ionized helium ions (He^{+}) and doubly ionized lithium ions (Li^{2+}).

'Electrons in atoms' is on the Block 7 DVD. You should start this activity now. When you have finished it, you should look at the summary in the comments on this activity.

Activity 5.1 Nucleons in nuclei

(*The estimated time for this activity is an hour and a half.*)

You have seen in Section 5 that there are several ways in which nuclei can change into other nuclei as a result of radioactive decay processes. But what determines which nuclei exist, and which of them are stable? And what determines the type of radioactive decay that an unstable nucleus undergoes, and how rapidly the decay takes place?

In this DVD-multimedia activity we provide you with a database of properties for all the possible stable and unstable nuclei in the Universe. Presented as a 'multilayered table', this database will enable you to investigate radioactive decay processes and find the answers to the questions above. Ultimately you will explore the 'valley of the nuclides', and will learn how the radioactivity of iridium may provide information about the demise of the dinosaurs.

As this is a long activity, you may wish to divide your study over a couple of sessions.

'Nucleons in nuclei' is on the Block 7 DVD. You should start this activity now. When you have finished it, you should look at the summary in the comments on this activity.

Activity 6.1 Quarks

(*The estimated time for this activity is 30 minutes.*)

In this activity you will investigate both strong and weak interactions, and see how combinations of quarks can be used to construct a variety of hadrons. The activity has three parts.

First, by examining strong interactions at the level of both hadrons and their constituent quarks you will see that the apparent random formation of pions from high-energy collisions of protons is governed by simple rules. Quarks and antiquarks are created out of energy and new particles appear as a result of their rearrangement.

In this part of this activity, you may find it useful to record, in Table 6.1.1, the details of the various particle collisions that you carry out. The first row in the table records the details of the first reaction described in the activity. (You may not necessarily fill every row.)

Table 6.1.1 To be completed during investigation of strong interactions in Activity 6.1.

Energy/MeV	Hadron picture		Quark picture	
	reactants	products	reactants	products
300	$p + p$	$n + n + \pi^+ + \pi^+$	$4u + 2d$	$4u + 4d + 2\bar{d}$
140	$P+P$	$n+p+\pi^+$	$4u+2d$	$4u+3d+1\bar{d}$
450	$P+P$	$P+P+\pi^+ +\pi^- +\pi^0$	$4u+2d$	$6u+3d+2\bar{u}+1\bar{d}$
550	$P+P$	$P+P+\pi^0 +\pi^0 +\pi^0$	$4u+2d$	$6u+3d+2\bar{u}+1\bar{d}$

When answering the questions in this activity about pion production, and deciding whether the reactions are allowed or not, you may find Table 6.1.2 useful for keeping track of the electric charge, energy and quark content of the particles listed in each question. The first box shows an example: electric charge is conserved as the charge on each side of the reaction is $+2e$; energy is conserved as the energy put in to the reaction is sufficient to create the products (any excess energy appears as kinetic energy of the products); and the number of quarks minus the number of antiquarks (for each flavour) is also conserved — so this reaction is allowed.

Table 6.1.2 To be completed when answering questions about pion production — which of the following reactions are allowed?

Example		
hadron reaction	$p + p + \text{energy} \longrightarrow n + n + \pi^+ + \pi^+$	
electric charge	$e + e \longrightarrow 0 + 0 + e + e$	OK
energy/MeV	$940 + 940 + 600 \longrightarrow 940 + 940 + 140 + 140$	OK
quark composition	$uud + uud \longrightarrow udd + udd + u\bar{d} + u\bar{d}$	OK
A		
hadron reaction	$p + p + \text{energy} \longrightarrow n + n + \pi^+ + \pi^+ + \pi^+ + \pi^-$	
electric charge		
energy/MeV		
quark composition		
B		
hadron reaction	$p + p + \text{energy} \longrightarrow n + n + \pi^+ + \pi^+ + \pi^0 + \pi^0 + \pi^0$	
electric charge		
energy/MeV		
quark composition		
C		
hadron reaction	$p + p + \text{energy} \longrightarrow n + p + \pi^+ + \pi^- + \pi^0 + \pi^0$	
electric charge		
energy/MeV		
quark composition		
D		
hadron reaction	$p + p + \text{energy} \longrightarrow n + p + \pi^+ + \pi^0 + \pi^0$	
electric charge		
energy/MeV		
quark composition		

In the second part of the activity, you will investigate the weak interaction that lies at the heart of nuclear β-decays. You will see that all such decays can be reduced to a fundamental process in which quarks change flavour, with the emission of a lepton–antilepton pair.

Finally, you will use a 'quark fruit machine' to simulate the way in which hadrons can be created from any combination of quarks and antiquarks that follow a few specific rules.

Throughout this DVD-multimedia activity, there are questions to help consolidate your understanding of this fundamental level of subatomic structure.

'Quarks' is on the Block 7 DVD. You should start this activity now. When you have finished it, you should look at the summary in the comments on this activity.

140
280
420
560
700

Activity 8.1 Making waves

(*The estimated time for this activity is 45 minutes, including about 25 minutes for watching the DVD-video sequence.*)

This DVD-video activity demonstrates important properties of waves using a ripple tank demonstration, animations and experiments with lasers. It also previews the practical work that you will be doing later in the block (Activity 10.1).

Whilst watching the DVD-video, you should make notes of the important properties of waves that are discussed. At a couple of points you are instructed to stop the sequence and carry out tasks related to what you have just seen. Details of these tasks are given below, together with photographs of still-frames from the DVD-video that you can use instead of taking measurements from the screen. (You may find it helpful to read through the notes on Task 1–3 in this activity before you watch the DVD-video.)

'Making waves' is on DVD 2 (DVD-video sequence 575–673). You should view this now.

Task 1 Determining the speed of a wave

Measure the wavelength and period of the wave from the graphs shown on the DVD-video (or in Figure 8.1.1). What is the frequency of this wave? Using these data, calculate the speed of the wave illustrated by these two graphs. ◀

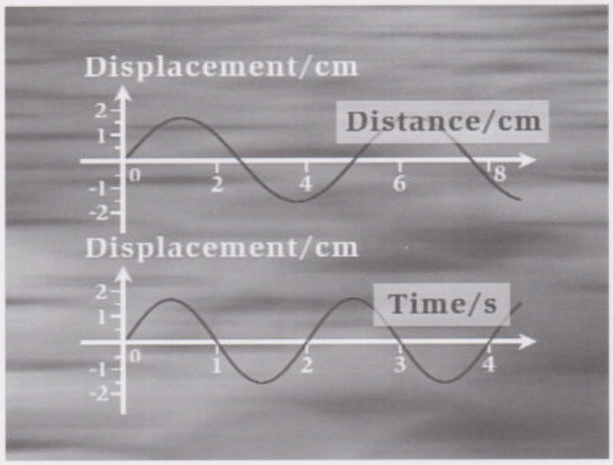


Figure 8.1.1 To be used with Task 1. A copy of the graph shown in the DVD-video. Notice that the mean displacement of this wave is zero. The displacement is measured above and below this mean level.

Task 2 The spread of a diffraction pattern: dependence on n

(a) Look at the diffraction pattern produced by the grating with $d = 10.0\ \mu m$, either on the television screen or in Figure 8.1.2. Measure the distances of the first six spots from the centre of the diffraction pattern (indicated by the zero on the scale) and record this information in Table 8.1.1. Remember that s_n refers to the distance to the nth spot, so s_1 is the distance to the first order spot, s_2 the distance to the second order spot, and so on.

(b) Look at the results that you have just obtained. If the order n is doubled, say from $n = 1$ to $n = 2$ or from $n = 3$ to $n = 6$, what happens to the distance of the diffraction spot from the centre of the pattern? Bearing this in mind, what can you say about the dependence of s_n on n? ◀

Task 3 The spread of a diffraction pattern: dependence on d

(a) Look at the diffraction patterns produced by the gratings with $d = 3.3\ \mu m$ and $d = 1.7\ \mu m$ (i.e. 300 lines per mm and 600 lines per mm, respectively) either on the computer or television screen or in Figure 8.1.2. Measure the distances of the *first* order spot from the centre of the diffraction pattern, in each case. Record your results, along with the corresponding distance for the first order diffraction spot from the grating with $d = 10.0\ \mu m$ (i.e. 100 lines per mm), in Table 8.1.2.

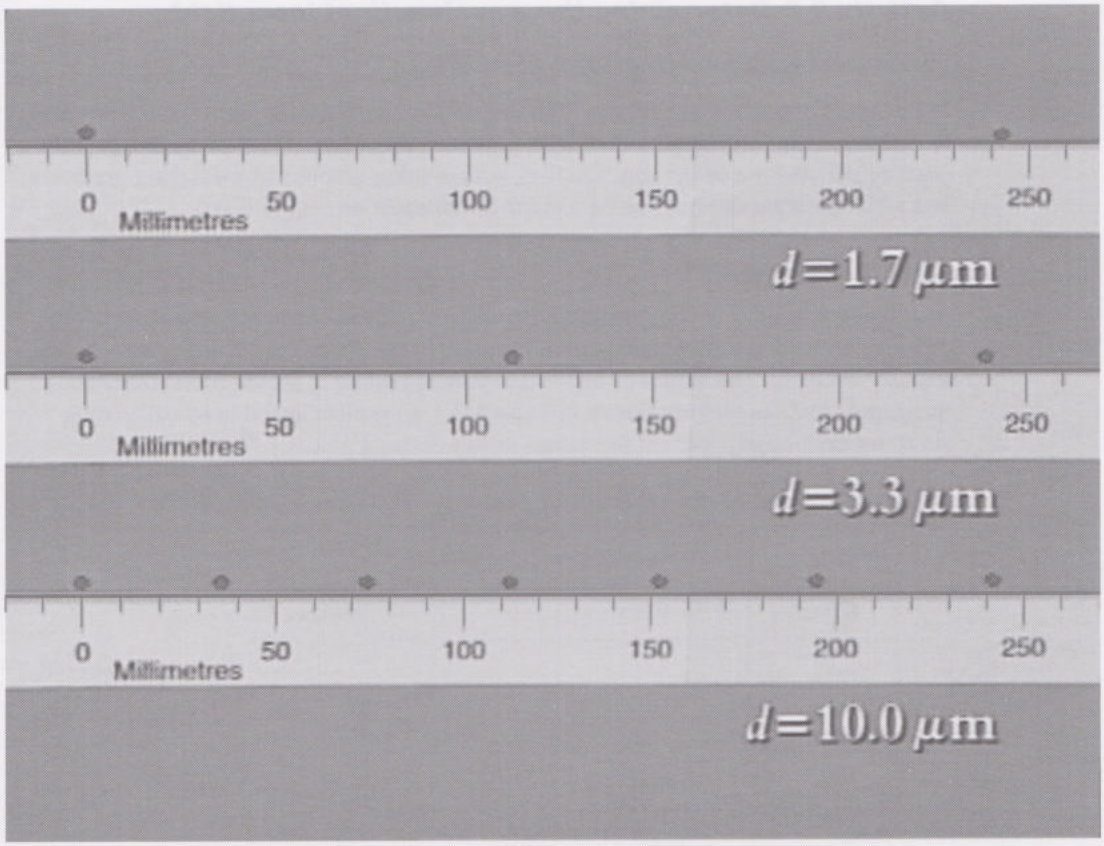


Figure 8.1.2 To be used with Tasks 2 and 3. A copy of the diffraction patterns shown in the DVD-video.

Table 8.1.1 Distances of spots from the centre of the diffraction pattern, using a grating with $d = 10.0\ \mu m$.

Order, n	Distance, s_n /mm
1	
2	
3	
4	
5	
6	

Table 8.1.2 Distances of the first order spots from the centres of the diffraction patterns, using three different gratings.

Line spacing, d /μm	Distance, s_1 /mm
10.0	
3.3	
1.7	

(b) The measurements in Table 8.1.2 are of a particular order of the diffraction pattern, $n = 1$, and with red light of a particular wavelength, but with a range of values for the line spacing of the grating, d. How does the distance of the first order spot in the diffraction pattern vary with d? What do you conclude about the dependence of the spread of the diffraction pattern, as quantified by s_n, on the line spacing of the grating, d? ◀

Activity 8.2 Determining the wavelength of laser light

(The estimated time for this activity is 15 minutes.)

In this activity you will use results from the DVD-video 'Making waves' (Activity 8.1) to determine the wavelength of red light produced by a laser. The activity will provide practice with the use of the sine function, with plotting graphs and measuring gradients, and with relating a straight line on a graph to the equation for the line.

Task 1 Calculating sin θ_n

In Activity 8.1, Task 2, you measured the distances of the diffraction orders from the centre of the diffraction pattern when a red laser beam illuminated a diffraction grating with $d = 10.0\ \mu m$. The angles of diffraction corresponding to these orders (measured to the nearest half-degree) are shown in Table 8.2.1. Complete the table by calculating $\sin \theta_n$ for each order. (Record the values to two decimal places.) ◀

Table 8.2.1 Diffraction data obtained with a red laser illuminating a grating with $d = 10.0\ \mu m$.

order, n	θ_n/degrees	$\sin \theta_n$
0	0.0	
1	3.5	
2	7.5	
3	11.0	
4	15.0	
5	18.5	
6	22.5	

Task 2 Plotting a graph

Equation 8.4 states that $\sin \theta_n = \dfrac{n\lambda}{d}$. For this set of data, the wavelength λ and the line spacing of the grating d do not change. The only quantities that vary from one measurement to the next are $\sin \theta_n$ and n. Bearing this in mind, use the values in Table 8.2.1 to plot a graph of $\sin \theta_n$ against n on Figure 8.2.1. (Refer to Block 2 Activity 5.1 and *SGSG* Maths Help 10, if necessary, for help with drawing graphs.) You may, if you wish, use this as an opportunity to try the S103 graph plotting package supplied on the Block 7 DVD.

As you saw in Block 3 Section 10.2.2, it is conventional to plot the so-called dependent variable, in this case $\sin \theta_n$, up the vertical axis of the graph, and the so-called independent variable, in this case n, along the horizontal axis. Choose a scale that makes as full a use as possible of the entire graph paper, but ensure that each centimetre division on the scale represents a 'sensible' number. For instance, two 1 cm divisions for every 0.1 change in $\sin \theta_n$ would be sensible since each division then represents 0.05. Three 1 cm divisions for every 0.1 change would not, since each division would then represent 0.033 33 and it would be more difficult to plot the data. ◀

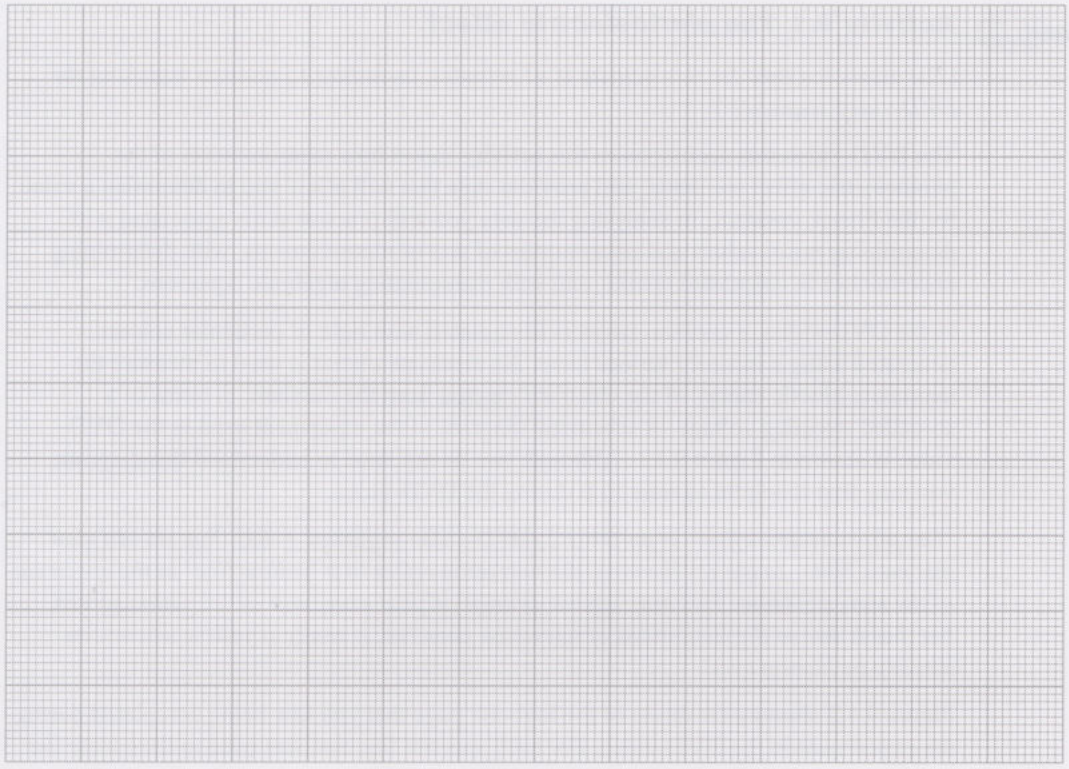


Figure 8.2.1 Graph paper for Task 2.

Task 3 The best-fit straight line

When you have plotted the points, draw what you consider to be the best-fit straight line through these data points. As you saw in Block 3 Activity 12.2, the best-fit straight line is the one that passes closest to most of the data points. Inevitably, some of the points will not fall on the straight line, but you should attempt to draw the line so that the points are fairly equally distributed on either side of it. ◀

Task 4 The gradient of a graph

The graph you have plotted of sin θ_n against n is a straight line passing through the origin, and this means that sin θ_n is proportional to n (Block 3 Box 12.1). This is what you might expect from Equation 8.4, $\sin\theta_n = \frac{n\lambda}{d}$, because if we write the equation as $\sin\theta_n = \left(\frac{\lambda}{d}\right) \times n$, and remember that both λ and d are constant for this set of data, then you can see that $\sin\theta_n \propto n$, or $\sin\theta_n = kn$, where the constant of proportionality $k = \frac{\lambda}{d}$. This shows that there is a straightforward relationship between sin θ_n and n, when both λ and d are constant, as is the case here. So Equation 8.4 is an equation of a straight line if sin θ_n is plotted versus n. (Refer back to Box 8.2 if you need help with this idea.) Writing Equation 8.4 as $\sin\theta_n = \left(\frac{\lambda}{d}\right) \times n$ makes it clear that the gradient of the graph you have just plotted is equal to $\frac{\lambda}{d}$.

You should now measure the gradient of the graph (see Block 3 Box 10.1), and use this value to calculate the wavelength of the red laser light. (Remember $d = 10.0\ \mu\text{m}$ for this grating.) ◀

Activity 9.1 The photoelectric effect

(*The estimated time for this activity is 45 minutes, including 15 minutes watching the DVD-video sequence.*)

The DVD-video that accompanies this activity shows how measurements of the photoelectric effect are made, and provides data that will allow you to determine a value for the Planck constant. In analysing the data you will practise skills associated with determining mean values and uncertainties of sets of measurements, with determining uncertainties in calculated results, and with manipulating algebraic equations.

In the DVD-video, a caesium target is illuminated with light of particular colours, generated using a mercury vapour lamp. An electrical circuit is used to measure the maximum kinetic energy of the electrons ejected from the caesium, in terms of a so-called stopping voltage. A schematic diagram of the equipment used in the DVD-video is shown in Figure 9.1.1. Although you do not need to understand this diagram, you may find it helpful to refer to it during the DVD-video.

'The photoelectric effect' is on DVD 2 (DVD-video sequence 1–63). You should view this now. Note: In the DVD-video, the narration refers to a 'yellow line' in the spectrum of the mercury lamp. This may appear orange on your computer or television screen, but that is due to the limitations of television cameras. It really is yellow when seen directly by human eyes!

Figure 9.1.2 shows a facsimile of the logbook page that you saw being completed during the experiment in the DVD-video. For each spectral line that was used to illuminate the caesium photocell, there are several measurements of the stopping voltage recorded. Notice that the individual values within each set of measurements are similar, but there is a certain amount of *scatter*. This scatter is a reflection of the difficulty in measuring the stopping voltage accurately and may be used to estimate the uncertainty in the final answer. One way to estimate the uncertainty from a range of measurements is discussed in Box 9.1.1, and you should study this box before tackling Task 1.

Box 9.1.1 Estimating the uncertainty from a range of values

If the measurement of a quantity during an experiment is repeated several times, it is unlikely that exactly the same value will be recorded on each occasion. This doesn't necessarily mean that any of the values are 'wrong' but simply reflects the difficulty in making the measurements. The best estimate of the 'true' value for the measured quantity is usually the mean of the individual values, and their scatter either side of this mean can be used to quantify the measurement uncertainty.

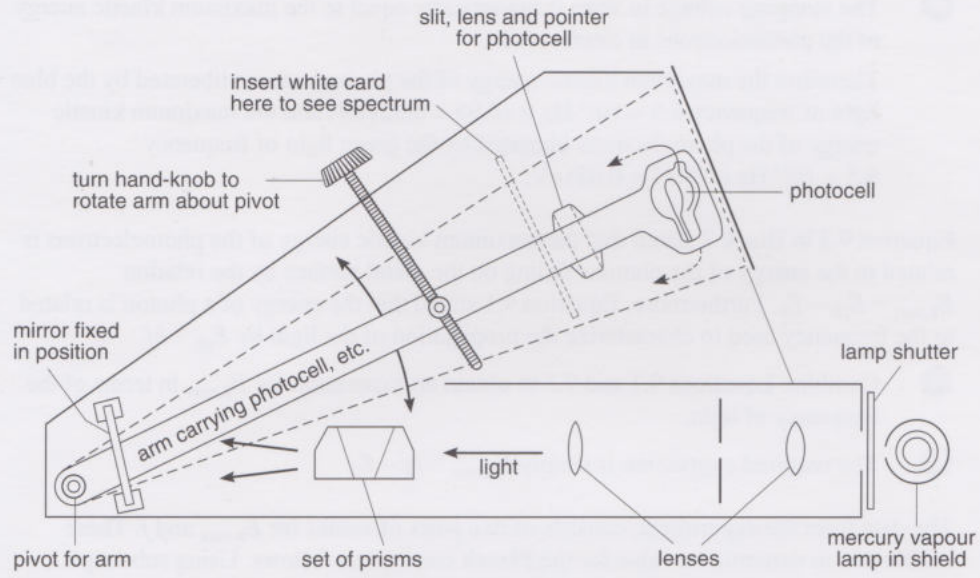
In a photoelectric effect experiment, for instance, suppose that the stopping voltages measured on six different runs with the same spectral line were: 0.52 V, 0.45 V, 0.46 V, 0.51 V, 0.40 V and 0.42 V. Then the mean stopping voltage is

$$\left(\frac{0.52 + 0.45 + 0.46 + 0.51 + 0.40 + 0.42}{6}\right) \text{V} = \left(\frac{2.76}{6}\right) \text{V} = 0.46 \text{ V}$$

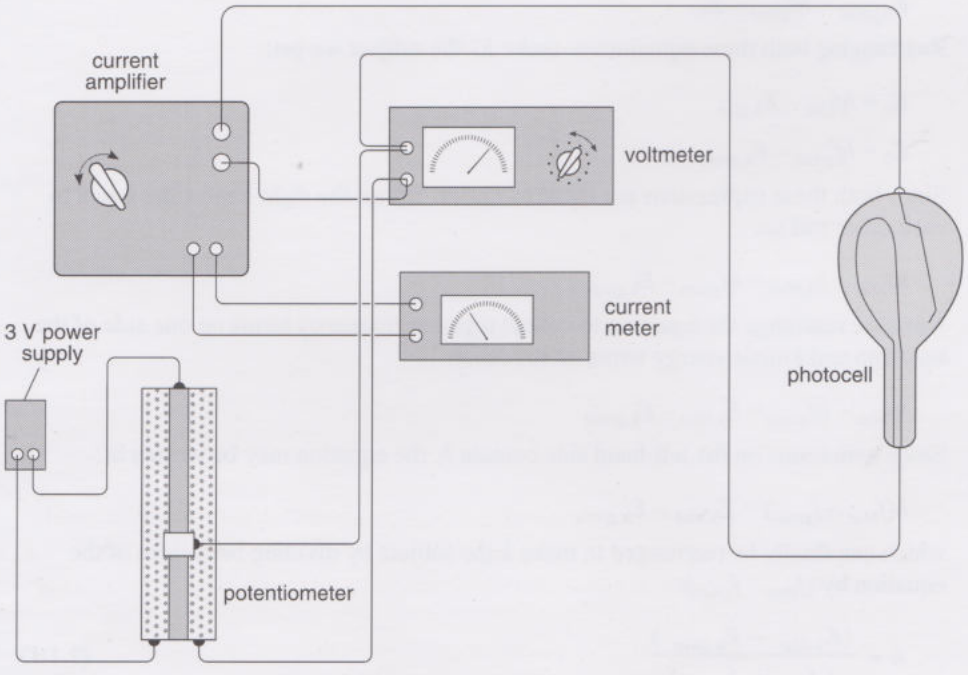
When many values of a single quantity have been recorded, as is the case here, it is unlikely that the 'true' value will be at the extremes of the range encompassed by all the data. So it is usually sufficient to say that the measurement uncertainty in the mean result is about two-thirds of the spread of the individual measurements about this mean.

The maximum value in the raw data here is 0.52 V, which is 0.06 V above the mean. The minimum value in the raw data is 0.40 V, which is 0.06 V below the mean. Two-thirds of the spread in this example is 0.04 V either side, so the mean stopping voltage may be written as 0.46 V ± 0.04 V. (It is often more convenient to write this as (0.46 ± 0.04) V.) In other words, if one more measurement were to be made, it is likely that it would fall within the range encompassed by the measurement uncertainty quoted here. The 'true' value of the stopping voltage, if it could be measured with infinite precision, would probably lie somewhere between 0.42 V and 0.50 V.

If the spread in values either side of the mean is slightly larger one side than the other, you should generally use the larger spread to estimate the uncertainty. Also, you should in general only quote uncertainties to one significant figure. For example, if the spread either side of the mean for a particular set of measurements was '0.73' then the uncertainty is $\frac{2}{3} \times 0.73 = 0.486\,667$ and should be quoted as '±0.5'. Any more significant figures than this would be misleading, since they would imply that you had some way to determine the uncertainty more precisely. Uncertainties in uncertainties are a complex subject and best left for higher level courses.



(a)



(b)

Figure 9.1.1 (a) Plan view of the optical apparatus used in the photoelectric effect experiment. (b) The electrical circuit used to measure the stopping voltage, and hence the maximum kinetic energy of the photoelectrons.

Task 1 Calculating mean values with measurement uncertainties

First, from Figure 9.1.2 calculate the mean value of the stopping voltage for each spectral line, and then determine approximate values for the measurement uncertainty for each of the mean stopping voltages that you have calculated. Write down the stopping voltage for each spectral line as 'mean ± uncertainty'. ◀

The **stopping voltage**, measured in volts, is the voltage required to stop any electrons from travelling round the circuit. As explained in the DVD-video, it is therefore numerically equal to the maximum kinetic energy of the photoelectrons, measured in electronvolts.

- What is the maximum kinetic energy of the electrons ejected from the caesium target by photons corresponding to each spectral line?
- The stopping voltage in volts is numerically equal to the maximum kinetic energy of the photoelectrons in electronvolts.

  Therefore the maximum kinetic energy of the photoelectrons liberated by the blue light of frequency 6.9×10^{14} Hz is (0.95 ± 0.02) eV; and the maximum kinetic energy of the photoelectrons liberated by the green light of frequency 5.5×10^{14} Hz is (0.37 ± 0.02) eV.

Equation 9.3 in Block 7 stated that the maximum kinetic energy of the photoelectrons is related to the energy of the photons falling on the metal surface by the relation $E_{k,max} = E_{ph} - E_0$. Furthermore, Equation 9.1 stated that the energy of a photon is related to the frequency used to characterize the propagation of the light by $E_{ph} = hf$.

- Combine Equations 9.1 and 9.3 to obtain an expression for $E_{k,max}$ in terms of the frequency of light.
- The required expression is simply $E_{k,max} = hf - E_0$.

The data from the experiment, consists of two pairs of values for $E_{k,max}$ and f. These enable you to determine a value for the Planck constant as follows. Using subscripts 'blue' and 'green' to represent the two sets of values, the equation above may be written as:

$$E_{k,blue} = hf_{blue} - E_0$$

$$E_{k,green} = hf_{green} - E_0$$

Rearranging both these equations to make E_0 the subject we get:

$$E_0 = hf_{blue} - E_{k,blue}$$

$$E_0 = hf_{green} - E_{k,green}$$

Since both these expressions are equal to E_0, we can set the right-hand sides equal to each other and so:

$$hf_{blue} - E_{k,blue} = hf_{green} - E_{k,green}$$

Next, we rearrange the equation to collect together frequency terms on one side of the equation and kinetic energy terms on the other:

$$hf_{blue} - hf_{green} = E_{k,blue} - E_{k,green}$$

Since both terms on the left-hand side contain h, the equation may be written as:

$$h(f_{blue} - f_{green}) = E_{k,blue} - E_{k,green}$$

which can finally be rearranged to make h the subject by dividing both sides of the equation by $(f_{blue} - f_{green})$:

$$h = \frac{(E_{k,blue} - E_{k,green})}{(f_{blue} - f_{green})} \qquad (9.1.1)$$

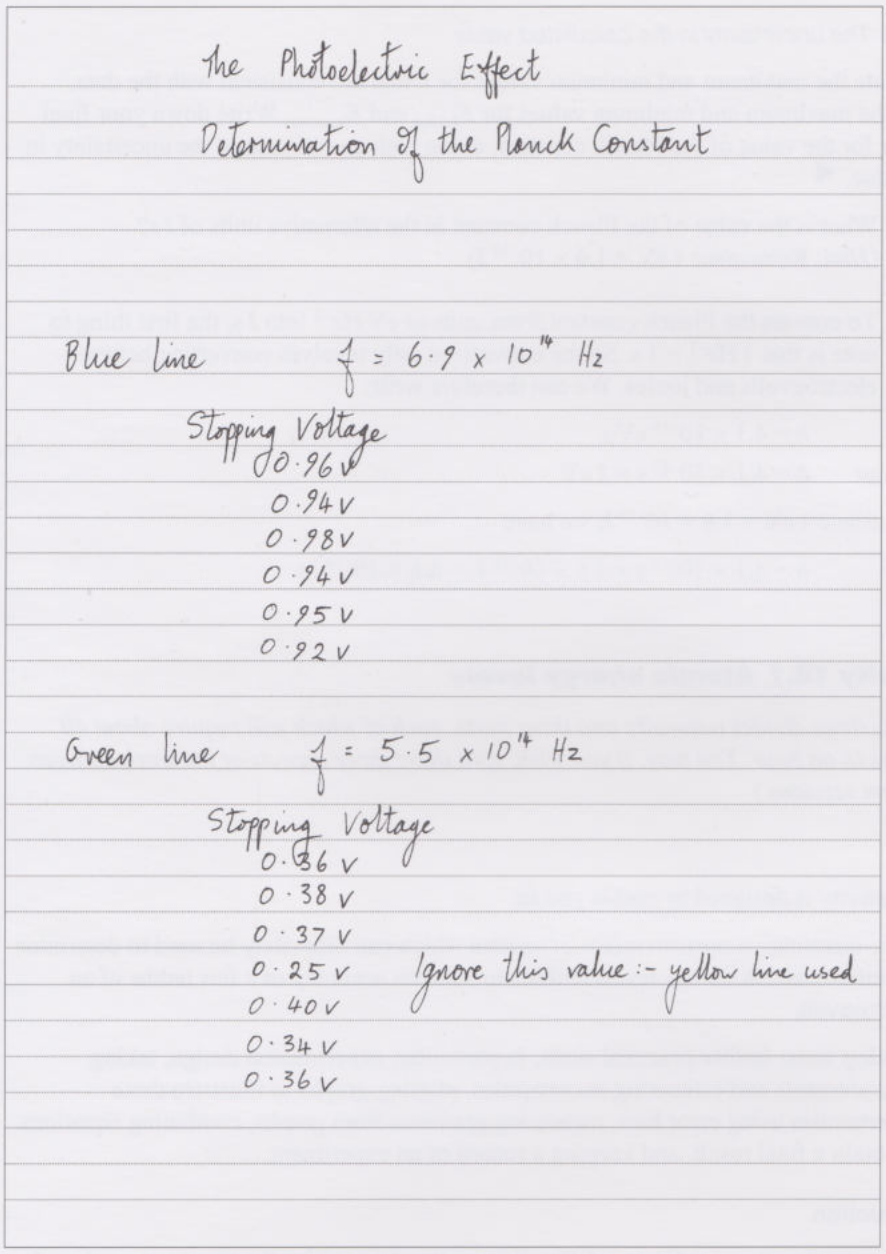


Figure 9.1.2 The logbook page completed during the photoelectric effect experiment.

Task 2 The value of the Planck constant

You should now substitute into Equation 9.1.1 the experimental results for the mean values of the maximum kinetic energy of the photoelectrons (from the answer to the question following Task 1) and the frequencies of the blue and green lines, and hence determine a value for h, the Planck constant, in units of electronvolts per hertz. ◀

Now look at the comments for Tasks 1 and 2 before continuing with this activity.

What about the measurement uncertainty associated with the value for the Planck constant? The simplest way to determine this is to calculate the maximum and minimum values of h that are consistent with the data. The maximum value of h consistent with the data is that calculated using the maximum value of $E_{k,blue}$ and the minimum value of $E_{k,green}$ (this makes the difference $E_{k,blue} - E_{k,green}$ as large as possible). The minimum value of h consistent with the data is that calculated using the minimum value of $E_{k,blue}$ and the maximum value of $E_{k,green}$ (this makes the difference $E_{k,blue} - E_{k,green}$ as small as possible).

Task 3 The uncertainty in the calculated value

Calculate the maximum and minimum values for h that are consistent with the data, using the maximum and minimum values for $E_{k,blue}$ and $E_{k,green}$. Write down your final answer for the value of the Planck constant, along with an estimate of the uncertainty in this value. ◀

What is the value of the Planck constant in the alternative units of J s? (*Hint*: Remember 1 eV = 1.6×10^{-19} J)

To convert the Planck constant from units of eV Hz^{-1} into J s, the first thing to note is that 1 Hz^{-1} = 1 s. So the conversion only involves converting between electronvolts and joules. We can therefore write:

$$h = 4.1 \times 10^{-15}\ \text{eV s}$$

or $$h = 4.1 \times 10^{-15}\ \text{s} \times 1\ \text{eV}$$

Since 1 eV = 1.6×10^{-19} J, we have

$$h = 4.1 \times 10^{-15}\ \text{s} \times 1.6 \times 10^{-19}\ \text{J} = 6.6 \times 10^{-34}\ \text{J s}$$

Activity 10.1 Atomic energy levels

(*This activity divides naturally into three parts, each of which will require about 40 minutes to an hour. You may, if you wish, split these three aspects of the work between different sessions.*)

Equipment (for Parts I and II)

KIT ITEMS
Diffraction grating
Paper protractor
(Study File pages 25 and 27)

NON-KIT ITEMS
Angle-poise lamp or table lamp
Standard, tungsten filament light bulb (60 W)
Energy saver light bulb (see Box 10.1.1, *Energy saver bulbs*)
Piece of stiff cardboard — a breakfast cereal box is ideal
Some books, dark cloth or cardboard to create a 'light-tight' enclosure
Blu-Tack
Thread or thin string (about 50 cm)
A pin or needle
A drawing pin
Modelling knife or sharp scissors to cut a *narrow* slit in the cardboard
Opaque tape (i.e. masking tape or insulating tape)

Aims

This activity is designed to enable you to:

- make quantitative measurements of spectra which can ultimately be used to determine the differences in energy levels within atoms to an accuracy of a few tenths of an electronvolt.
- develop some further practical skills, in particular, experimental design, taking measurements and estimating uncertainties, plotting graphs to illustrate these uncertainties using error bars, measuring gradients from graphs, combining equations to obtain a final result, and keeping a record of an experiment.

Introduction

In this experiment you will use a diffraction grating to examine the spectrum produced by an energy saver light bulb. After making a qualitative description of the spectrum (Part I), and comparing it with the spectrum of light from a standard, tungsten filament, light bulb, you will measure, in Part II, the angles of diffraction for certain spectral lines that are present. In Part III you will use these angles of diffraction to determine the wavelength of the light corresponding to these lines. You will then convert these wavelengths into the corresponding frequencies, and finally into energies in electronvolts. These energies are then identified with the differences between energy levels of atoms.

We have provided tables that you can use to record your data, but you should also record how you did the experiment and any difficulties that arose. There will also be things that you want to write down that we have not thought of, so we suggest that you keep notes in your Study File. *As you do the experiment* write down anything that you think is important. Include all of your results — don't be tempted to miss something out because you think that it is wrong. Also make a note of things that you find difficult, and things that you think that you could do better if you were to repeat the experiment. If a TMA question is set asking you to write up this experiment, then you can base your report on the notes you make now.

Box 10.1.1 Energy saver bulbs

Energy saver bulbs are becoming increasingly common around the home and elsewhere. Whilst being as bright as conventional tungsten filament bulbs, they consume typically less than 20% or so of the power, and last far longer. A report from the Consumers Association in December 1995 estimated that an 11 W energy saver bulb would save £35 over its lifetime, when compared with the costs of buying and powering conventional tungsten filament light bulbs. Not only do these bulbs save you money, but since they use far less power, you use far less electricity, and so power stations release far less greenhouse gases into the atmosphere as they generate less electricity!

A selection of the bulbs that are suitable for this activity are shown in Figure 10.1.1. They come from a variety of manufacturers but are all around 10 to 12 W power rating, and are reasonably lightweight. You may already have an energy saver bulb in your home, and whatever its type it will probably be suitable for this activity. If not, you will have to buy one, but you can then of course use it in your home for years to come.

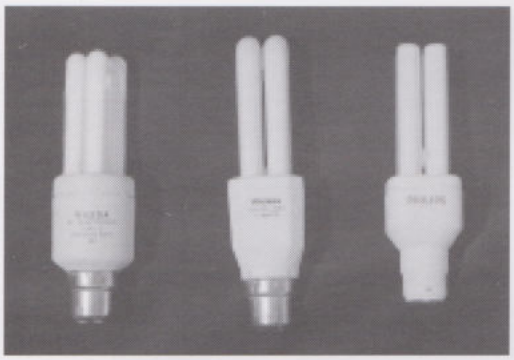


Figure 10.1.1 A selection of energy saver bulbs suitable for Activity 10.1. From left to right they are: Mazda 4L Electronic (12 W), Wickes Low Energy (11 W), Philips PL Electronic C (11 W).

Part I Observing the diffraction patterns

The first part of this activity involves setting up the equipment and making some initial, qualitative, observations of diffraction patterns.

First, read through the notes for Part I, and then return to this point and carry out the instructions.

Safety precautions: since this experiment involves using household light bulbs which will become hot, please read the advice contained in the *Practical Work Booklet* concerning the first aid treatment of burns *now*.

Practical procedure

The first step is to gather together the equipment listed at the start of the activity.

This experiment is best carried out in a darkened room (total darkness is not necessary), and ideally you should carry it out on a steady surface, such as a large table, at least 1 m long. You will need about a metre of clear space at one end of the table to move around whilst taking measurements. If it is a nice table, protect it with a cloth!

An angle-poise lamp is best for this activity as it allows greater flexibility, but a small table lamp is also adequate. A tungsten filament light bulb is the normal type of bulb that you will have around your house. Energy saver bulbs are becoming increasingly common and should be available from your local supermarket or hardware shop if you don't have one already (see Box 10.1.1, *Energy saver bulbs*).

The diffraction grating is mounted in the small flat object that looks something like a 35 mm photographic slide. The lines of the grating run parallel to its shorter side, and the

line drawn on the slide mount is parallel to the grating lines. So the grating should be used with this line vertical.

Start by cutting a narrow, vertical slit near the bottom edge of the piece of cardboard. Ideally this should be about 50 mm long and about 0.5 to 1 mm wide, with sharp, straight edges. (You may wish to practise cutting this first with a spare piece of cardboard.) If you have trouble cutting a slit that narrow, use two pieces of *opaque* tape (insulating tape for instance) stuck along the edges of a wider slit to reduce its width. Alternatively, you may be able to fold two pieces of kitchen foil over a wider slit to make it narrower, and straight edged. The purpose of the slit is to restrict the size of the light source that you will be observing through the diffraction grating. Be inventive!

As shown in Figure 10.1.2, place your lamp at one end of the table and insert into it the tungsten filament light bulb. Arrange the lamp so that the bulb is no more than about 5 cm above the table surface. If you use an angle-poise lamp, bend it down close to the table and point the bulb forwards so that it is parallel to the table surface. If you use a table lamp, you may find it easiest to remove the shade and stand the lamp on a chair just below the level of the table surface, so that the bulb just sticks up above the table. When you have the lamp in place, plug it in and switch on the power.

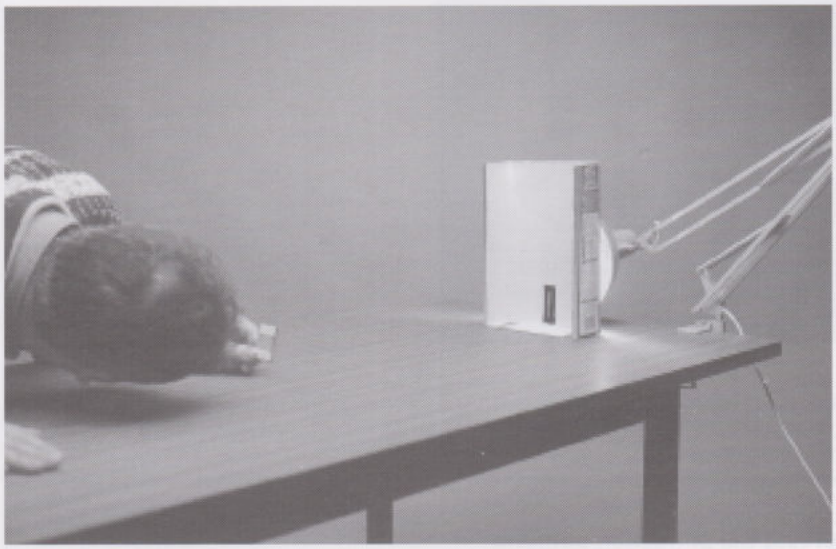


Figure 10.1.2 Making the initial observations. Note that the 'light-tight' housing has been omitted here to enable you to see the position of the lamp.

Next arrange the piece of card so that its slit is fixed vertically between you and the light source. Blu-Tack may be used to hold the card in place, or you may be able to prop it up using books. Ensure that the narrow slit is aligned *vertically* and that the card is not too close to the bulb, else it may become hot — a distance of between 10 cm and 20 cm should be okay. The bottom edge of the card should be in contact with the table so that no light passes underneath it.

It will certainly help if you can build a 'light-tight' housing around the sides and top of the lamp and slit arrangement. You might use more cardboard, books or a dark cloth for this purpose, but be careful to keep all such items at least 10 cm away from the bulb itself or they may become very hot. The only light you see should be that which emerges through the slit. Stray light may will lead to distractions and complications when taking the measurements. Again, be inventive!

Task 1 The diffraction pattern of a tungsten filament bulb

Having set up the equipment, squat down so that your eye line is level with the slit, and simply hold the diffraction grating up close to one eye (as shown in Figure 10.1.2). From a distance of about one metre, look *through* the grating towards the slit in the card and the light emerging through it. As you look through the grating, concentrate on the light that appears either side of the slit, and at the same height as the slit (any other light you see will be due to leakage).

Make a few notes describing what you can see as you look through the grating towards the slit. A sketch may help you to identify some of the features. Some of the things that you might comment on are:

- How many *orders* of the diffraction pattern are visible?
- Is the pattern identical to the left and right of the centre?
- How are the colours distributed within each diffraction order?
- What does the zero order, in the centre of the pattern, look like?

Now switch off the power to the lamp, and wait for the bulb to cool down for a few minutes. ◀

Now look at the comments on Task 1 before continuing with this activity.

Task 2 The diffraction pattern of an energy saver bulb

Replace the tungsten filament light bulb with the energy saver bulb. (Be careful handling the tungsten filament bulb if it is still hot.) Examine closely the spectrum of this new light source, in the same way that you did for the tungsten bulb.

Make a few notes describing what you can see as you look through the grating towards the slit at the energy saver light bulb. As in Task 1, a sketch may help, and some of the things that you might comment on are:

- How many *orders* of the diffraction pattern are visible?
- Is the pattern identical to the left and right of the centre?
- How are the colours distributed within each order?
- What features can you see *within* each order of the diffraction pattern?
- What does the zero order, in the centre of the pattern, look like? ◀

Before you move on to the next part of this activity, look at the comments on Task 2 and then try the following questions to consolidate your understanding of these spectra. (The answers are given in the comments section.)

Question 10.1.1 (a) How do the spectra of the two bulbs differ from the spectra of the lasers that you saw being used in Activity 8.1?

(b) What terms would you use to describe the types of spectra produced by each type of light bulb? ◀

Question 10.1.2 From what you have seen of the spectra of tungsten light bulbs and energy saver light bulbs (both here and in Section 7), can you suggest why the latter are more energy efficient? ◀

Part II of this activity involves taking measurements of the spectrum of the energy saver light bulb. If you are going to continue with Part II straightaway, leave the equipment set up. However, if you plan to do Part II at some other time, you should bear in mind that you will need to use all the equipment again in Part II.

Part II Measuring diffraction angles

Read through the notes for Part II now, then return to this point and carry out the instructions.

The aim of this part of the investigation is to determine the wavelengths of the various lines in the spectrum of the energy saver light bulb. To do this you will need to devise a means of measuring the angle of diffraction of each spectral line, in each order of the diffraction pattern. You may like to consider for yourself how you might do this. One suggestion is provided below, but do feel free to devise your own method that may give more accurate results.

Practical procedure

If necessary, set up the equipment again as you did for Part I and, if you don't already have them, gather together the additional pieces of equipment needed for Part II.

We have provided you with a paper protractor with an angular scale marked in degrees. This is printed on page 25 of this Study File (with a duplicate supplied on page 27).

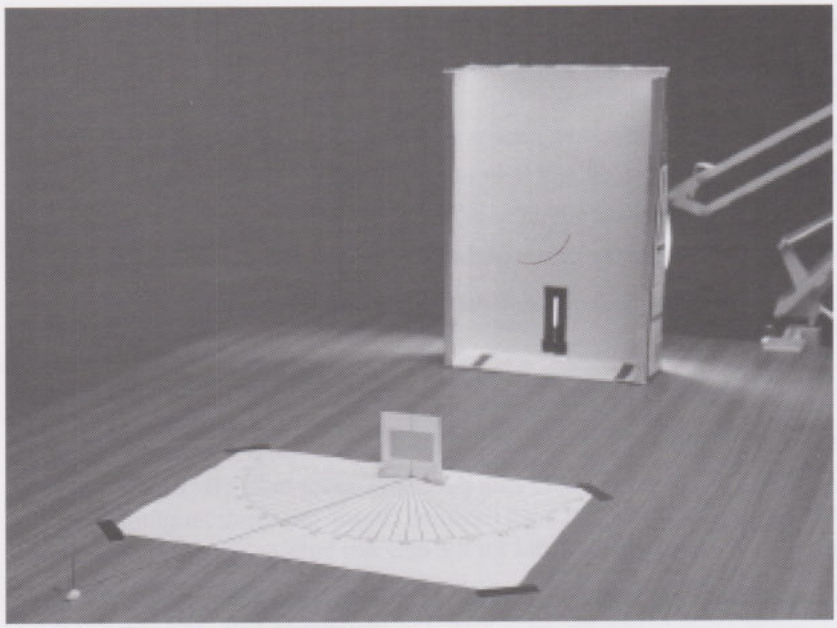


Figure 10.1.3 A possible method for measuring the angle of diffraction of each spectral line. Again, the light-tight housing around the lamp has been omitted.

Figure 10.1.3 illustrates one possible method for determining the angles of diffraction. If you use this method, you should proceed as follows.

Push a drawing pin from the back of the paper through the axis of the paper protractor (the point where all the lines converge, marked by a dot) and then stick the paper protractor to the table using tape or Blu-Tack, about a metre away from the lamp and slit. (The head of the drawing pin should be in contact with the table, with the point sticking up through the paper!) Make sure that the flat edge of the protractor is closest to, and parallel to, the piece of card that contains the slit, and that the zero degree line of the protractor is pointing directly towards the slit (see Figure 10.1.3).

Next fasten a length of thread or thin string to the drawing pin; about 50 cm should be sufficient. Dark coloured thread will probably show up best against the white paper of the protractor.

There is a line drawn on the diffraction grating marking an axis through its centre. Make sure that this line is facing you and, using Blu-Tack, mount the diffraction grating along the flat edge of the protractor, so that the line is vertical and is as close as possible to the drawing pin which marks the protractor's axis.

The protractor and grating should remain fixed in position throughout the experiment once everything is aligned correctly.

Finally, tie a pin or needle to the free end of the thread. Stick the end of the pin in a piece of Blu-Tack to make it easier to hold.

Now, when you look through the grating towards the slit, and move your head from side to side, you will see the bright lines in the spectrum of the energy saver bulb. In Task 3 you will be asked to determine the angle of diffraction for particular lines. To try out this procedure you should move your head from side to side and at the same time find a position for the pin or needle that allows you to line up: a spectral line, the line drawn on the diffraction grating, and the pin or needle at the end of the thread. You will have to close one eye for this (to avoid so-called parallax effects) and should make sure that the thread remains taut. You may find this easier with one eye than the other — so try both! When you have achieved this alignment, the thread will register the angle of diffraction θ_n on the scale of the protractor.

Remember that an angle of diffraction of zero degrees corresponds to the straight through position, and so should correspond to the position of the zero order — the slit itself. Make sure that the slit does indeed correspond to an angle of zero degrees on the protractor. If it does not, adjust the position of the card containing the slit, until it does.

The aim of the experiment is to determine the wavelengths of several spectral lines. As noted in the comments on Task 2, you should be able to see three orders of the spectrum

on either side of the central position, possibly four, but the lines may well be brighter on one side than the other. Within each order you can probably see at least four or five reasonably bright emission lines along with many fainter ones. The brightest are probably the blue, green and red lines as shown in Colour plate 10.1.1. (Please refer to the labels on this figure, and decide which lines in your spectra correspond to the named colours.)

You can, of course, measure angles of diffraction for spectral lines to the left *and* right of the centre of the pattern and these angles should be equal. For instance, the angle of diffraction of the green line in the second order spectrum to the *left* of the centre should be the same as the angle of diffraction of the green line in the second order spectrum to the *right* of the centre.

However you choose to determine θ_n for each spectral line, the measurement will have an associated uncertainty. It is impossible to measure the angles precisely since the protractor only registers angular divisions of a degree, although you may be able to estimate angles to the nearest half-degree. For the fainter, or more diffuse lines, the uncertainty in your measurements may well be larger than for those lines that are brighter, or more sharply defined.

Task 3 Measuring angles of diffraction

Bearing in mind the general comments above, measure the angles of diffraction of the blue, green and red lines in each of the first, second and third order spectra in the diffraction pattern (and the fourth order if you can see it) and record the angles in Table 10.1.1. You may find it useful to have a torch handy when you record the measurements, particularly if you have blacked out all other light sources. Remember, for each angle, include an estimate of the measurement uncertainty. To save time, you should measure the angles on just one side of the zero order (either to the right or to the left, whichever is brighter). However, you may wish to check quickly, for one or two lines, that the angles are similar on each side of the pattern. (The last two columns of Table 10.1.1 will be filled in Task 4.) ◀

Table 10.1.1 For use in Tasks 3 and 4 to record angular measurements.

Order, n	θ_n/degrees	Uncertainty in θ_n/degrees	sin θ_n	Uncertainty in sin θ_n
Blue spectral line				
1				
2				
3				
4				
Green spectral line				
1				
2				
3				
4				
Red spectral line				
1				
2				
3				
4				

Check your values for the diffraction angles against the values given in Table 10.1.2 in the comments before you dismantle the equipment.

Having determined the value of θ_n for the different orders n for each of three spectral lines in Task 3, you can now proceed to calculate the wavelengths of these lines. You

will not need to take any more measurements at this stage, unless you want to go back and check any results, so you may want to pack away the equipment and find somewhere more convenient to complete this work.

Part III Determining the photon energies of the spectral lines

The final part of the activity involves analysing the results you have just obtained.

Before you start this part of the activity, read through the notes as far as the end of Task 9.

Determining the wavelength

The stages in determining the wavelengths of each spectral line are:

- to calculate values for $\sin\theta_n$ corresponding to each diffraction angle that you measured in Part II;
- to plot graphs of $\sin\theta_n$ against n to find the best-fit straight line through the data;
- to measure the gradient of each of these graphs and so calculate the wavelength of each spectral line.

Task 4 Calculating $\sin\theta_n$

For each value of θ_n that you have measured for each spectral line, calculate $\sin\theta_n$. Write these values in the fourth column of Table 10.1.1, quoting them to two significant figures in each case.

To take account of the uncertainty in your measured angles, be sure to calculate a *range* of values for $\sin\theta_n$ in each case. For example, if you measured a certain angle to be $\theta_n = 15° \pm 1°$, then the maximum value of $\sin\theta_n$ that is consistent with your measurement is $\sin 16° = 0.28$, and the minimum value of $\sin\theta_n$ that is consistent with your measurement is $\sin 14° = 0.24$. Since $\sin 15° = 0.26$, the value of $\sin\theta_n$ that you would record in the table is 0.26 and the uncertainty in $\sin\theta_n$ is ± 0.02 in this case.

For some angles, the upper limit to $\sin\theta_n$ may not be the same distance from the mean value, as the lower limit to $\sin\theta_n$. For instance, if $\theta_n = 41° \pm 2°$, then the mean value for the sine of the angle is 0.66, and the upper and lower limits are 0.68 and 0.63, respectively. In this case it is probably best to overestimate the total uncertainty and to express the result as 0.66 ± 0.03. Write the uncertainties in each value of $\sin\theta_n$ in the fifth column of Table 10.1.1. ◀

Now check your values with those in Table 10.1.2 in the comments for Task 4 before continuing with this activity.

Task 5 Plotting graphs with error bars

Now, on Figure 10.1.4 plot a graph for each of the three sets of results that you have obtained. These can all go on the same set of axes for convenience. As in Activity 8.2, it is conventional to plot the measured variable, in this case $\sin\theta_n$, up the vertical axis of the graph, and the independent variable, in this case n, along the horizontal axis.

Uncertainties can be expressed on a graph by drawing what is known as an **error bar** at each point. An error bar represents the full range of a value that is consistent with what is measured. For example, if you have recorded a particular value as $\sin\theta_n = 0.26 \pm 0.02$, then you would plot it on a graph as shown in Figure 10.1.5. The error bar extends from $\sin\theta_n = 0.26 - 0.02 = 0.24$ up to $0.26 + 0.02 = 0.28$. It shows that the true value of $\sin\theta_n$ could be anywhere within this range. Plot error bars for each of your measured values.

There is an extra point that you can plot for each set of data. Remember that the zero order of the diffraction pattern is coincident with the bright, white, vertical line in the centre of the pattern — the slit in the card. All light, whatever its wavelength, appears at this same position in the pattern. The angle of diffraction of the zero order is 0° and $\sin 0° = 0$. So on your graph the point where $n = 0$ and $\sin\theta_n = 0$ should also be plotted.

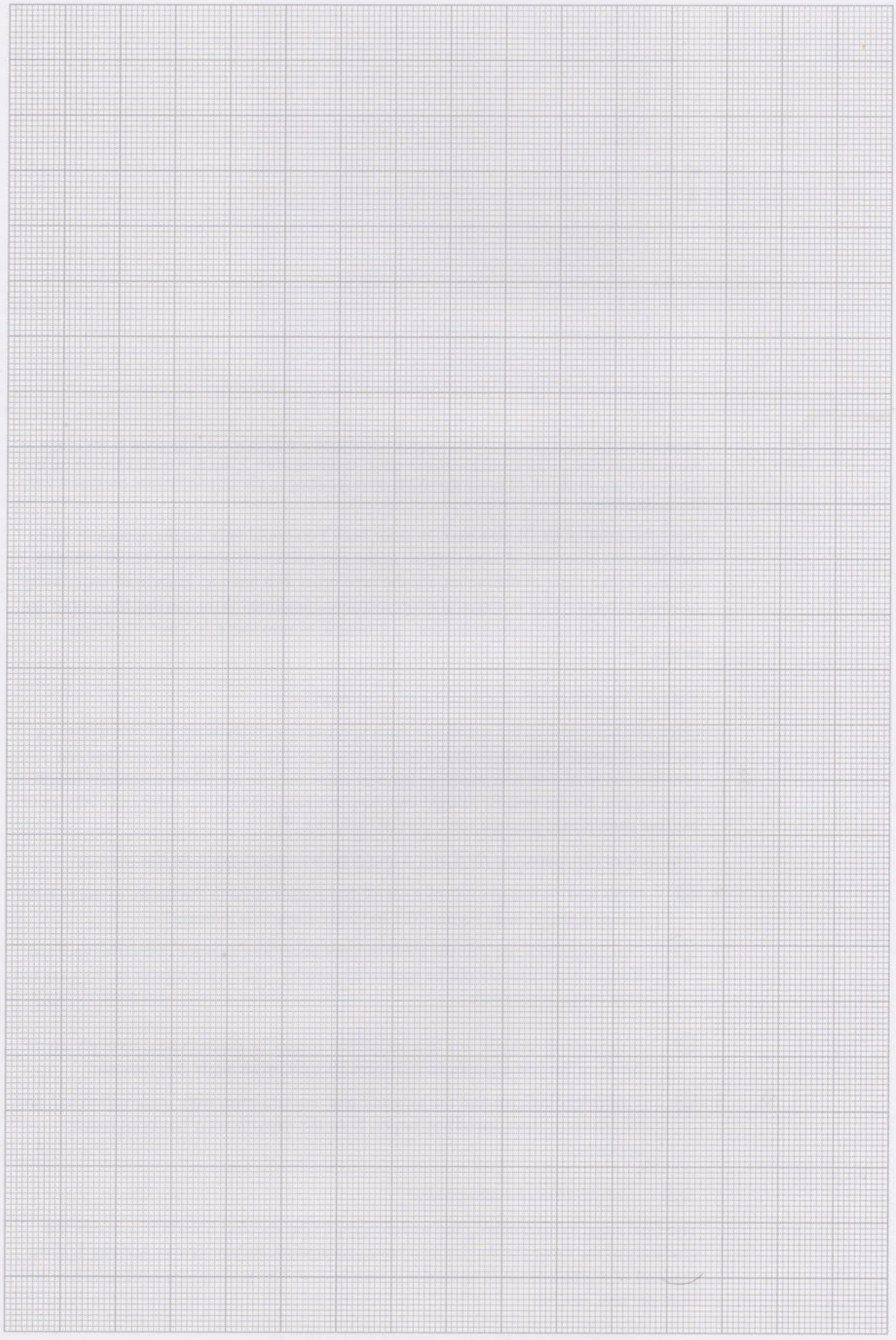


Figure 10.1.4 Graph paper for Task 5.

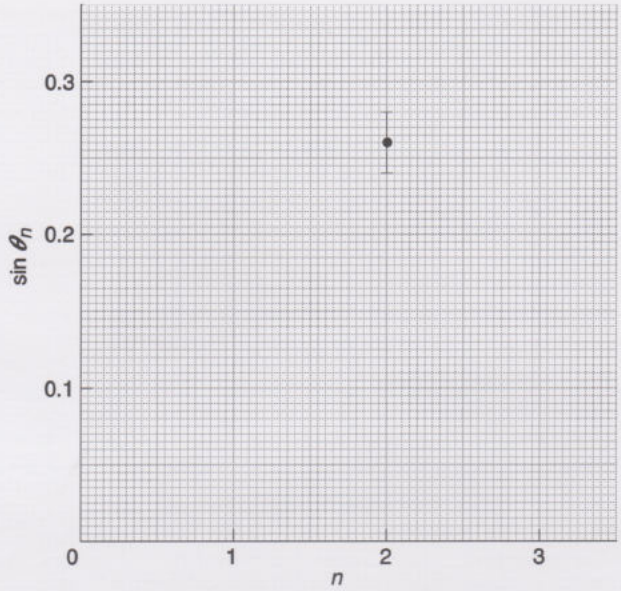


Figure 10.1.5 The error bar for the result sin $\theta_n = 0.26 \pm 0.02$ at $n = 2$. The point in the centre of the error bar corresponds to the measured value, in this case $n = 2$, sin $\theta_n = 0.26$. The vertical line stretches from sin $\theta_n = 0.28$ to sin $\theta_n = 0.24$, corresponding to the range of values consistent with the measurement.

Does this point at (0, 0) also have an error bar? You could only set the apparatus up so that the zero order was at zero degrees to the precision with which you could measure angles. So the angle of diffraction for the zero order will have an associated uncertainty of about the same size as those of other measured positions. You can therefore draw an error bar for the zero order point that is similar in size to those on your other data points. ◀

Task 6 The best-fit straight line to a set of data points

Once you have plotted the graphs for each spectral line, draw what you consider to be the best-fit straight line through the data. Remember that the error bars indicate the possible *range* of a measurement — the true value may lie anywhere within the length of the error bar. So the best-fit straight line need not pass through the *centre* of every error bar, but should pass through some part of each one. ◀

Now look at the comments for Tasks 5 and 6 before continuing with this activity.

If the best-fit straight line to a set of data passes close to the centre of every error bar on a graph, as in Figure 10.1.6a, what might this indicate?

This might indicate that the measurement uncertainties were *overestimated*, and the true error bars should be somewhat smaller. The experimenter in this case has been rather pessimistic!

If the best-fit straight line to a set of data cannot be made to pass through any of the error bars on a graph, as in Figure 10.1.6b, what might this indicate?

This might indicate that the measurement uncertainties were *underestimated*, and the true error bars should be larger. Now the experimenter has been rather optimistic!

Task 7 The gradient of a straight line

The final stage in determining the wavelengths of the spectral lines is to measure the gradients of the three graphs that you have just plotted. As you saw in Activity 8.2, the gradient of a graph of sin θ_n against n is simply λ/d. The grating you have used has 300 lines per mm, and so

$$d = \frac{1}{300\ \text{mm}^{-1}} = 3.33 \times 10^{-3}\ \text{mm, or } 3.33 \times 10^{-6}\ \text{m}$$

which may be written as 3.33 μm. Measure the gradient of each graph, and so calculate the wavelength of each spectral line that you measured. ◀

Now look at the comments for Task 7 before continuing with this activity.

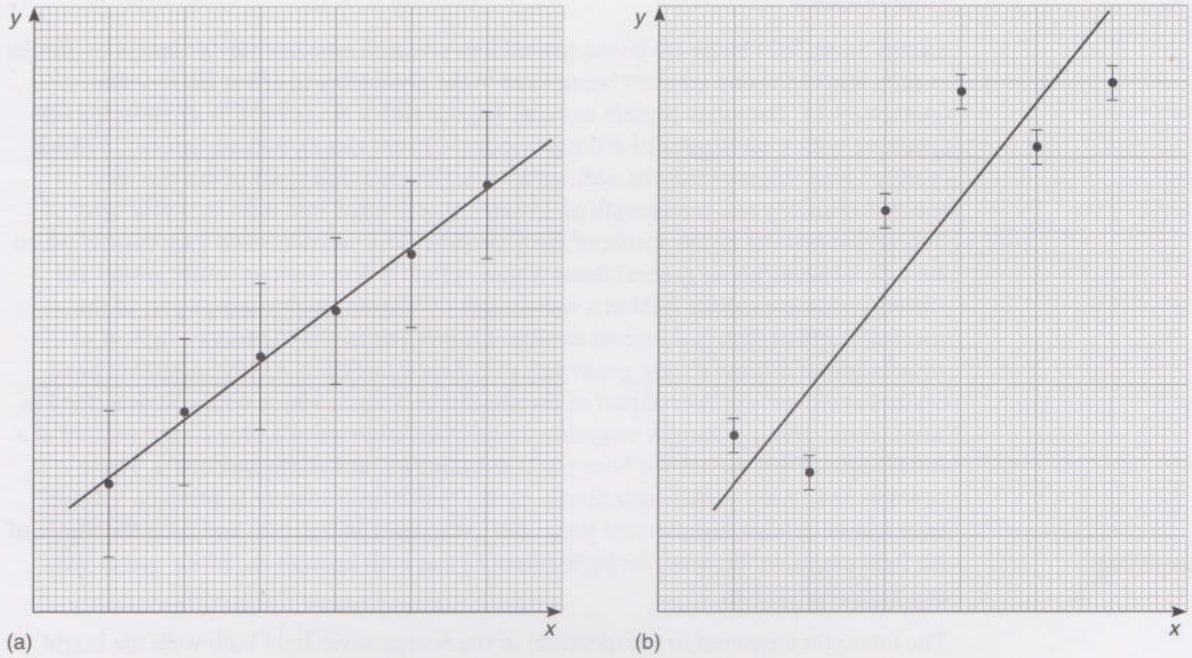


Figure 10.1.6 (a) An example of overestimated error bars. (b) An example of underestimated error bars.

To determine the wavelengths of the red, green and blue spectral lines produced by the energy saver bulb, you measured the angles of diffraction for each line in *each* order of the diffraction pattern. What is the advantage of this technique over taking a single angular measurement in a *single* order of the diffraction pattern and then calculating the wavelength of each line directly using $\lambda = \frac{d \sin \theta_n}{n}$?

Taking just a single measurement of the angle of diffraction may lead to the possibility of a significant error in the measurement. This could arise simply due to a measuring mistake for instance. By taking angular measurements in each order of the diffraction pattern, and then plotting a graph of the results, the effect of this source of error is reduced, and you will also notice if one point is badly out of line with the others. The values you have obtained for the wavelengths of the spectral lines are derived from an average of all the measurements that you took, and a single discrepant result therefore has less effect on the final values.

Also, by plotting the uncertainty in each measurement as an error bar on the graph, you can take account of the uncertainties in a simple way when drawing the best-fit straight line. In general, in any practical work, taking several measurements and determining values graphically, so averaging over all readings, is to be preferred over taking just a single measurement.

Determining the frequency and photon energy

You have now determined the wavelength of each of three spectral lines in the spectrum produced by an energy saver light bulb. The final step is to relate these wavelengths to the energy carried by the photons.

Task 8 Converting wavelengths into frequencies

Using Equation 8.2 from Block 7, $c = f\lambda$, calculate the frequency corresponding to each of the wavelengths that you have calculated. (You may assume that $c = 3.0 \times 10^8\ \text{m s}^{-1}$.)

Task 9 Converting frequencies into energies

Using Equation 9.1 from Block 7, $E_{\text{ph}} = hf$, calculate the energy, in electronvolts, corresponding to each of the frequencies that you have just calculated. (You may assume that $h = 4.1 \times 10^{-15}\ \text{eV Hz}^{-1}$.)

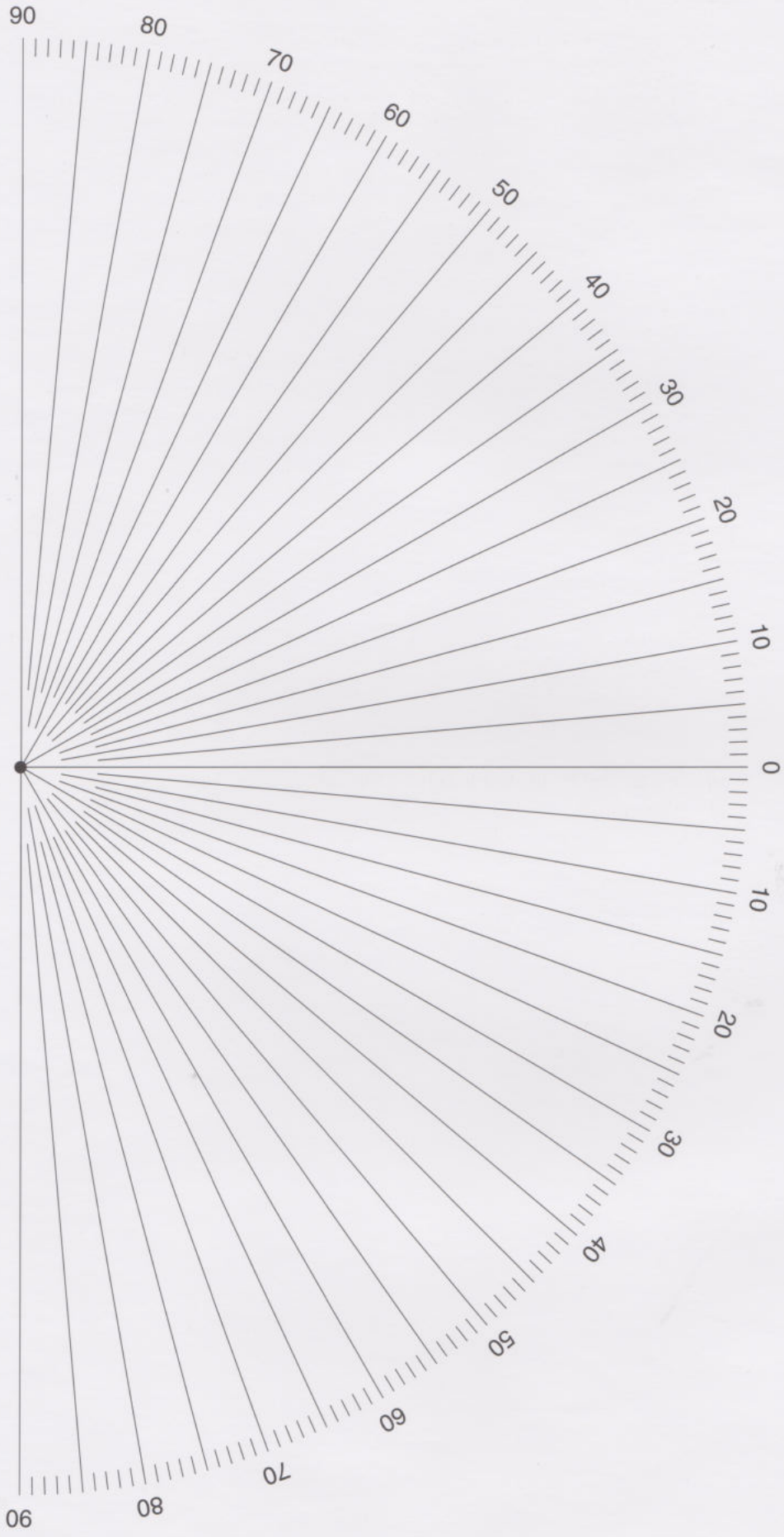
Now look at the comments for Tasks 8 and 9 before continuing with this activity.

Final remarks

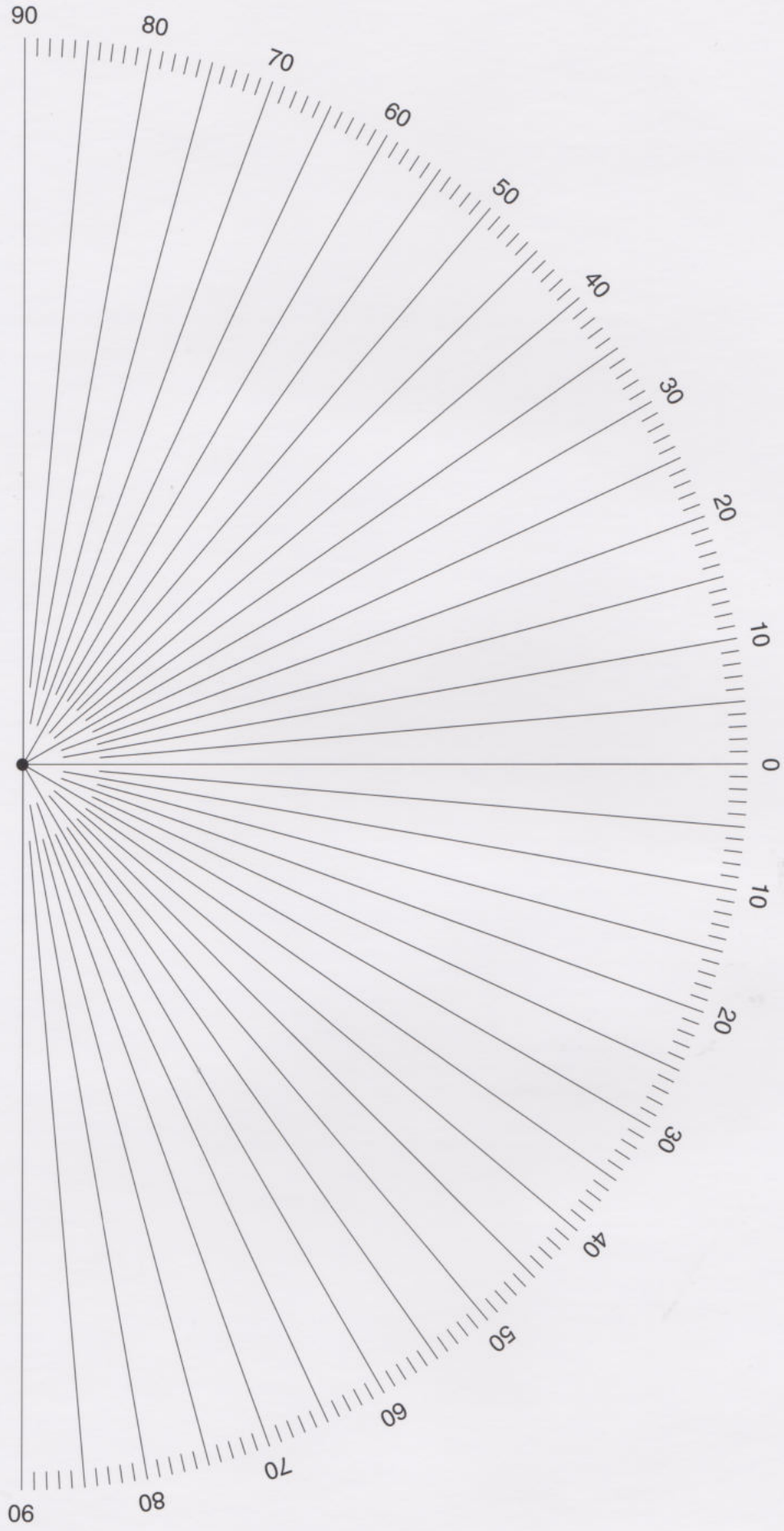
Energy saver light bulbs are based around low-pressure mercury vapour lamps — similar in principle to the one you saw being used in the photoelectric effect DVD-video (Activity 9.1). The tubes contain mercury vapour which emits light as an emission line spectrum with wavelengths of 405 nm (violet), 436 nm (blue), 546 nm (green), 578 nm (yellow), and 618 nm (red). In addition to this, the ultraviolet part of the mercury spectrum (mainly at a wavelength of 254 nm) is converted into light by a thin layer of fluorescent powder on the inside of the glass tube. The powders used vary depending on the type of lamp, but in general those whose colour is described as 'warm white' use yttrium oxide to produce light at a wavelength of 610 nm (in the orange part of the spectrum) and cerium gadolinium terbium magnesium borate to produce light at a wavelength of 542 nm (in the green part of the spectrum) plus a broad emission band centred at 623 nm (in the red part of the spectrum). Lamps whose colour is described as 'cool white' also use barium magnesium aluminate to produce a broad band centred at a wavelength of 447 nm (in the blue-green or turquoise part of the spectrum). These powders have been chosen specifically by the bulb manufacturers to produce spectral lines whose colours complement those due to the mercury vapour, and span the whole of the light range. In this way, the light output by the bulb appears as 'white' rather than any particular colour.

The lines you measured in the spectrum of the energy saver light bulb were the bright blue, green and red lines. From the description above, you can see that these lines have wavelengths of 436 nm, 542–546 nm, and 618 nm, respectively. The equivalent photon energies, corresponding to radiation of these wavelengths, are 2.84 eV, 2.28 eV and 2.01 eV, respectively. According to Equation 2.1, $E_{ph} = \Delta E_{atom}$, these energy values in turn represent the differences in energy between pairs of allowed energy levels for the mercury atoms and other compounds mentioned above.

You may have noticed that many street lamps emit a yellow light. As noted earlier in the block, this is because they contain a vapour consisting of sodium atoms. When the vapour is excited by an electric current, the sodium atoms make transitions between different quantum states, causing the atoms to lose energy, and so photons are emitted. The difference in energy of the levels principally involved in these transitions is 2.1 eV. This gives rise to light whose wavelength is 590 nm, which corresponds to the yellow part of the visible spectrum. If you get the chance, look at some street lamps through the diffraction grating, and observe the strong yellow line in their spectrum.



Paper protractor for use with Activity 10.1 Part II. (Duplicate copy supplied on page 27.)



Paper protractor for use with Activity 10.1 Part II. (Duplicate copy supplied on page 25.)

Activity 10.2 Reflections on the practical work

The experiment which you have just completed in Activity 10.1 is the longest and most complicated home experiment in this course. So pause for a minute to reflect on what you have achieved, both in terms of the results you have obtained, and in terms of any new skills which you have developed.

(a) Were your results reasonably close to the values given in the 'Final remarks' section? (You will have to decide what is 'reasonable' here. Remember that the equipment that you used was not terribly sophisticated and there will have been several contributing uncertainties.)

(b) A list of skills developed or practised in this activity is given in Table 10.2.1. Tick the appropriate cell in each row of the table to rate your own ability in each of these skills.

Table 10.2.1 Skills developed or practised in Activity 10.1.

Skill	Having real problems	Still struggling	Fairly confident	Confident	Very confident
Understanding instructions					
Setting up apparatus, and modifying it if necessary					
Taking measurements					
Estimating uncertainties					
Plotting graphs with error bars					
Drawing best-fit straight lines					
Calculating the gradient of a straight-line graph					
Relating the gradient of a graph to the equation of a straight line					
Combining and rearranging algebraic equations					
Keeping a record of an experiment					

Activity 11.1 Reviewing your study of Block 7: dealing with difficult material

(a) (i) Make a list of the models that have been introduced in previous blocks and another list of the models that you have used to help you to understand the 'beyond common sense' ideas of Block 7. Your lists will contain many different sorts of models (you may remember that you considered two different sorts of model in Block 2 Activity 9.5).

(ii) Now think for a few minutes about how you use models.

- Think about the leaky tank analogy in Block 2, and try to decide why this was useful to you.
- Now think about the Bohr model of the atom. Was this useful in the same way?
- Do these two examples allow you to make any generalizations about how you use models?
- If you were able to generalize, think about whether your generalizations apply to any of the other models you listed in part (i).

(iii) Do the models that have been introduced in the course have any limitations? You may find this easiest to answer if you start by thinking about limitations of specific models, and then generalizing as in (ii).

(iv) Have you invented any models of your own to help you to understand the material introduced in this block?

(b) The use of modelling was just one of the strategies for 'dealing with difficult material' introduced in Block 6 Activity 15.1 and revisited in Block 7 Activity 3.2. Have you made any further additions to your tool kit of techniques for dealing with difficult concepts, or had any opportunities to test any of your strategies?

Comments on activities

Activity 2.1

One student's response to the questions posed in parts (a) and (b) was as follows.

> (a) I used to think that light was a wave. I suppose this goes back to what I learnt — or at least thought I learnt — at school. This is also what earlier blocks of the course have said. Now this block says that light is made up of particles called photons. This seems most bizarre.
>
> (b) We are told that atoms can only absorb or emit photons with certain energies, which means that the 'internal' energy of an atom only has certain allowed energy levels. The evidence from line spectra that atoms only absorb or emit photons with certain energies seems quite convincing to me, and the explanation of this in terms of allowed energy levels in atoms also seems reasonable, but *why* should atoms only be allowed to have certain energy levels? This just doesn't seem to make sense.

Note that the nature of light is discussed more fully in Sections 7–10 of this block, and we will start to answer the question 'why do atoms have energy levels?' in the next section.

(c) We will discuss models of the atom in Section 3, and you will be able to review how your mental picture has changed at the end of that section.

To be read after you have completed Section 3

(d) Diagrams illustrating the Rutherford model, Bohr model and Schrödinger model are shown in Figure 2.1.1. The Rutherford model has electrons orbiting the nucleus in much the same way that planets orbit the Sun, and these electrons can move from one orbit to another orbit of any radius. In the Bohr model only certain orbits (corresponding to the different energy levels) are allowed. In the Schrödinger model, the electrons don't travel in orbits and can be found *anywhere*.

Which model was your picture closest to? Before reading about the ideas introduced in Section 3, most people would probably draw something like the Rutherford model — our ideas of mini-solar systems are deeply embedded. Some people, after reading Section 2, might have modified the Rutherford model to produce something like the Bohr model, identifying quantized energy levels with allowed orbits of fixed radius. And some people, who have read about quantum physics before, might have drawn something like Figure 2.1.1c, with the fuzzy electron cloud.

(e) You may have written something like:

> Quantum indeterminacy means that it is not possible to predict definitely the outcome of any individual measurement when there is more than one possible outcome.

Quantum indeterminacy is incorporated into the Schrödinger model, where electrons can be anywhere, and you can only specify the probability that they will be found in a particular region. Neither the Rutherford model nor the Bohr model take account of quantum indeterminacy, but this does not mean that these models are completely wrong. According to the Schrödinger model, the electron in a hydrogen atom may be found at any distance from the nucleus. However, for the ground state of hydrogen, the probability of finding the electron at a certain distance from the nucleus is highest for a distance that corresponds to the radius of the ground state orbit in the Bohr model. So the Bohr model contains an element of truth — you have to be very careful not to throw out the baby with the bath water!

You also need to remember that a model can continue to be useful even when you know that it is not a very accurate representation of the truth. Think back to the modelling you have done earlier in the course. In Block 2 you used the leaky tank analogy to help understand the energy balances that determine the Earth's GMST. But this does not mean that the Earth really is a leaky tank! It is sensible to use the model which is most helpful for the problem in hand. The Bohr model, with electrons in fixed orbits, may have its shortcomings, but thinking in these terms will be adequate for the molecular science covered in later blocks of the course.

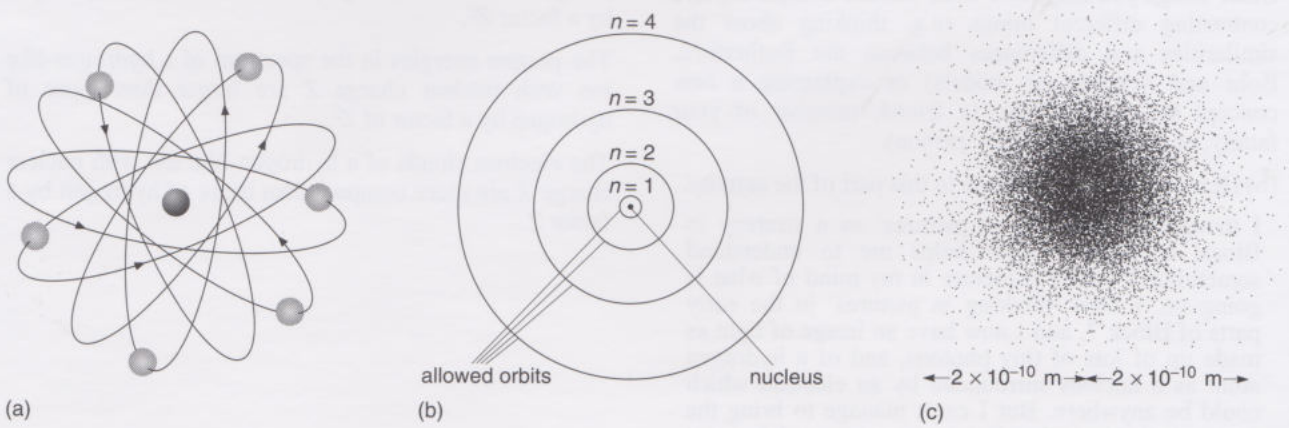


Figure 2.1.1 Three models of an atom: (a) the Rutherford model; (b) the Bohr model; (c) the Schrödinger model.

Activity 3.1

The completed table is shown as Table 3.1.2. A dash (–) indicates that a particular combination of n and l quantum numbers is not allowed.

Table 3.1.2 Completed version of Table 3.1.1. Quantum states of hydrogen.

n	l					E_n/eV	Total number of states
	0	1	2	3	4		
1	1s	–	–	–	–	–13.60	2
2	2s	2p	–	–	–	–3.40	8
3	3s	3p	3d	–	–	–1.51	18
4	4s	4p	4d	4f	–	–0.85	32
5	5s	5p	5d	5f	5g	–0.54	50
Number of states for each l	2	6	10	14	18		

Activity 3.2

(a) Activity 2.1 encouraged you to use certain techniques in dealing with difficult material. These techniques include:

- comparing what you thought previously with what you think now (light, energy of atoms, models of the atom);
- thinking about the evidence you have been given, and how this changes your ideas (for energy levels in atoms);
- thinking in terms of models (Rutherford, Bohr, Schrödinger);
- drawing diagrams to help you to visualize the situation (sketch of your model of an atom);
- explaining your diagrams in words;
- explaining a difficult concept in your own words (quantum indeterminacy);
- thinking about the application of a difficult concept (quantum indeterminacy in the Schrödinger model).

Quite often you may feel that you don't understand something, but when you work with it and apply it to a new task, you start to feel that you have a glimmering of what it is all about. Making use of new ideas in different contexts is a good way to become more familiar with them, and to understand them better.

Other things you may have done include comparing and contrasting different things (e.g. thinking about the similarities and differences between the Rutherford, Bohr and Schrödinger models) or explaining a new concept to someone else (a friend, member of your family, or even an imaginary person).

(b) Here is a student response to this part of the activity.

> I thought of 'thinking in pictures' as a strategy in Block 6. It very often helps me to understand something if I have a picture in my mind of what is going on. I used 'thinking in pictures' in the early parts of Block 7, and I now have an image of light as made up of lots of tiny photons, and of a hydrogen atom as a nucleus surrounded by an electron which could be anywhere. But I can't manage to bring the concept of energy levels into my picture. I have to accept that I can't think of a picture for everything, and sometimes I have to remind myself that my pictures aren't necessarily right.
>
> I like to try explaining things to other people. I hadn't thought of that before, but I tried explaining quantum ideas to my mother, which was very hard because she hasn't studied any science. I'm not sure that she really understood what I was talking about, but trying to get the basic ideas across to her certainly helped me to understand them better! I hope that I'll get a chance to talk to some other students about these quantum ideas at the tutorial next week.

(c) The student who responded in part (b) is developing modelling as a learning technique. Many more models will be introduced in Block 7 and we will return to the use of modelling as a method for dealing with difficult concepts in Activity 11.1.

Note that, as we described in Block 6 Activity 15.1, what you need to do is to test your learning techniques in different situations, and to modify and refine these techniques, and to be prepared to apply and modify them again and again in new situations. This is part of the learning cycle described in *SGSG* Chapter 1 Section 4.2.

Activity 4.1

Summary of 'Electrons in atoms'

The energy levels of a hydrogen-like ion with nuclear charge Z are more widely spaced than those of hydrogen by a factor Z^2.

The photon energies in the spectrum of a hydrogen-like ion with nuclear charge Z are larger than those of hydrogen by a factor of Z^2.

The electron clouds of a hydrogen-like ion with nuclear charge Z are more compact than those of hydrogen by a factor Z.

Activity 5.1

Summary of 'Nucleons in nuclei'

Nuclei of atoms are composed of *nucleons*, i.e. protons and neutrons. The total number of nucleons in a particular nucleus is the *mass number A*, the number of protons is the *atomic number Z*, and the number of neutrons is the **neutron number** *N*. A nucleus with a particular combination of *N* and *Z* is referred to as a **nuclide**. Nuclides with the same atomic number but different mass numbers, as a result of containing a different number of neutrons, are referred to as isotopes.

The *N*–*Z* chart (reproduced in Colour plate 5.1.1) containing all possible nuclides shows that stable nuclides form a narrow ribbon, bending slowly upwards as *N* gradually outnumbers *Z*. Pairing of both neutrons and protons is favoured in stable nuclides, and nuclides with even numbers of protons tend to be more abundant.

Either side of the narrow ribbon of stable nuclides is a wide band containing unstable nuclides, which undergo radioactive decay.

- In α-decay, an α-particle (nucleus of helium-4) is emitted so reducing *N* by 2 and *Z* by 2.
- In β^--decay, an electron and an electron antineutrino are emitted so increasing *Z* by 1 and decreasing *N* by 1.
- In β^+-decay, a positron and an electron neutrino are emitted so decreasing *Z* by 1 and increasing *N* by 1.
- In **electron capture** the nucleus captures an electron and emits an electron neutrino so decreasing *Z* by 1 and increasing *N* by 1.

In each case the **parent nuclide** decays into a **daughter nuclide** with a different combination of *A* and *Z*.

The most massive nuclides are prone to undergo **nuclear fission** in which a nuclide splits into two roughly equal bits and releases a few neutrons. These free neutrons can trigger further fissions and so initiate a chain reaction.

In order to determine which decays are possible, it is useful to define the **mass excess** of a nuclide. Radioactive decays will only occur if the mass excess of the daughter nuclide is less than the mass excess of the parent nuclide.

The *N*–*Z* chart can be converted into another representation by plotting the mass excess of each nuclide as a third dimension — height. This reveals the so-called *valley of the nuclides* in which unstable nuclides are found up the sides of the valley, and stable ones along the valley floor. Radioactive decays involve progressions down the sides of the valley; the steeper the sides of the valley, the faster the rate of decay.

Radioactive decay is a random process. A plot of the radioactive count rate, measured in an experiment, against time reveals a falling **exponential** curve. This allows us to define the **half-life** of a radioactive sample as the time taken for the activity of the sample to fall by half, or equivalently the time taken for half the nuclei in a radioactive sample to decay. A plot of the radioactive count rate against the number of radioactive nuclei remaining in a sample is a straight line, showing that the probability for a given nucleus to decay remains constant.

Activity 6.1

Summary of 'Quarks'

Reactions involving strong interactions may be interpreted as the rearrangement of quarks between hadrons, accompanied by the creation, or annihilation, of quark–antiquark pairs. For instance, pions containing a pair of up and down quarks and antiquarks are created in collisions between protons. They each have a mass of $140\,\text{MeV}/c^2$ and so require 140 MeV of energy in order to be created. Just which pions are created in a given collision is subject to the rules of quantum indeterminacy: whatever is allowed to occur will do so, sooner or later.

For instance, in collisions between protons at an energy of about 500 MeV, the following outcomes are all possible:

$$p + p \longrightarrow n + p + \pi^+$$

$$p + p \longrightarrow p + p + \pi^0$$

$$p + p \longrightarrow n + n + \pi^+ + \pi^+$$

$$p + p \longrightarrow n + p + \pi^+ + \pi^0$$

$$p + p \longrightarrow p + p + \pi^0 + \pi^0$$

$$p + p \longrightarrow p + p + \pi^+ + \pi^-$$

$$p + p \longrightarrow n + n + \pi^+ + \pi^+ + \pi^0$$

$$p + p \longrightarrow n + p + \pi^+ + \pi^+ + \pi^-$$

$$p + p \longrightarrow n + p + \pi^+ + \pi^0 + \pi^0$$

$$p + p \longrightarrow p + p + \pi^+ + \pi^- + \pi^0$$

$$p + p \longrightarrow p + p + \pi^0 + \pi^0 + \pi^0$$

Further quantum indeterminacy is illustrated by the fact that each neutral pion can have a quark composition that is either $u\bar{u}$ or $d\bar{d}$.

Weak interactions involve the transformation of one flavour of quark into another flavour, with the emission of a lepton–antilepton pair. For instance, in β^--decay a down quark transforms into an up quark with the emission of an electron and an electron antineutrino; whilst in β^+-decay an up quark transforms into a down quark with the emission of a positron and an electron neutrino.

The following reactions therefore lie at the heart of all β-decays:

$$d \longrightarrow u + e^- + \bar{\nu}_e$$

$$u \longrightarrow d + e^+ + \nu_e$$

All hadrons are composed of quarks. Any combination of three quarks is a baryon, any combination of three antiquarks is an antibaryon, and any combination of a quark and an antiquark is a meson. Unlike quarks, which have fractional electric charges, all hadrons have whole-number electric charges.

possible charge of a baryon:	$+2e, +e, 0, -e$
possible charge of an antibaryon:	$+e, 0, -e, -2e$
possible charge of a meson:	$+e, 0, -e$

Activity 8.1

Task 1

The upper graph (in Figure 8.1.1) shows the displacement against distance at an instant of time, so it can be used to measure the wavelength. The lower graph shows the displacement against time at a fixed point in space, so it can be used to measure the period. The wavelength is $\lambda = 5.0$ cm and the period of the wave is $T = 2.0$ s. So the frequency of the wave is

$$f = \frac{1}{T} = \left(\frac{1}{2.0}\right) s^{-1} = 0.50 \text{ Hz}$$

The speed of propagation of the wave is therefore $v = f\lambda = 0.50 \text{ Hz} \times 5.0 \text{ cm} = 2.5 \text{ cm s}^{-1}$.

Task 2

(a) Table 8.1.3 shows some typical results which should be similar to those you have measured.

(b) Looking at the results in Table 8.1.3, you can see that as the order is doubled, say from $n = 1$ to $n = 2$, or from $n = 3$ to $n = 6$, so the distance of the spot from the centre of the pattern also (approximately) doubles. Similarly, the third order of the diffraction pattern is about three times further from the centre than the first order of the diffraction pattern, and so on. The results show that the distance s_n is roughly *proportional* to the order n of the diffraction pattern. Notice, however, that the proportionality becomes increasingly approximate as s_n becomes large.

Table 8.1.3 Completed version of Table 8.1.1. Distances of spots from the centre of the diffraction pattern, using a grating with $d = 10.0$ μm.

Order, n	Distance, s_n/mm
1	37
2	74
3	112
4	152
5	195
6	241

Task 3

(a) Table 8.1.4 shows some typical results, and your measured values should be similar to these.

(b) Looking at the results in Table 8.1.4, you can see that as d is *reduced* by a factor of three, from $d = 10.0$ μm to $d = 3.3$ μm, so the distance of the first order spot from the centre of the diffraction pattern *increases* roughly by a factor of three. Similarly, as d is *halved* from $d = 3.3$ μm to $d = 1.7$ μm, so s_n is approximately doubled. The results indicate that the distance s_n is roughly proportional to $1/d$. Alternatively, we may say that, roughly speaking, s_n is *inversely proportional to d* (Block 7 Box 8.1).

Table 8.1.4 Completed version of Table 8.1.2. Distances of the first order spots from the centres of the diffraction patterns using three different gratings.

Line spacing, d/μm	Distance, s_1/mm
10.0	37
3.3	112
1.7	243

Activity 8.2

Task 1

A completed set of data is shown in Table 8.2.2.

Table 8.2.2 Completed version of Table 8.2.1. Diffraction data obtained with a red laser illuminating a grating with $d = 10.0$ μm.

Order, n	θ_n/degrees	$\sin\theta_n$
0	0.0	0.00
1	3.5	0.06
2	7.5	0.13
3	11.0	0.19
4	15.0	0.26
5	18.5	0.32
6	22.5	0.38

Tasks 2 and 3

A graph of the data is shown in Figure 8.2.2. To make maximum use of the paper, a convenient vertical scale is one 1 cm division for every 0.05 in $\sin\theta_n$, and a convenient horizontal scale is one 1 cm division for every 0.5 in n. Notice that the best-fit straight line does not pass through all the points, but some are above the line and some below it.

Task 4

The line passes through the points (1.25, 0.08) and (6.25, 0.40). So the gradient of the line is:

$$\frac{\text{rise}}{\text{run}} = \frac{0.32}{5.00} = 0.064$$

Since neither $\sin\theta_n$ nor n has any units associated with them, the gradient has no unit either.

Now, Equation 8.4 states that $\sin\theta_n = \left(\frac{\lambda}{d}\right) \times n$, so the gradient of a graph of $\sin\theta_n$ against n will be equal to $\frac{\lambda}{d}$. In this case, $d = 10.0$ μm, so the wavelength is

$$\lambda = d \times \text{gradient} = (10.0 \text{ μm}) \times 0.064 = 0.64 \text{ μm}$$

The wavelength of the red laser light is therefore 0.64 μm, or 0.64×10^{-6} m, or 6.4×10^{-7} m. Your own answer should be within a few per cent of this value. In fact, the wavelength of the laser is actually 6.36×10^{-7} m

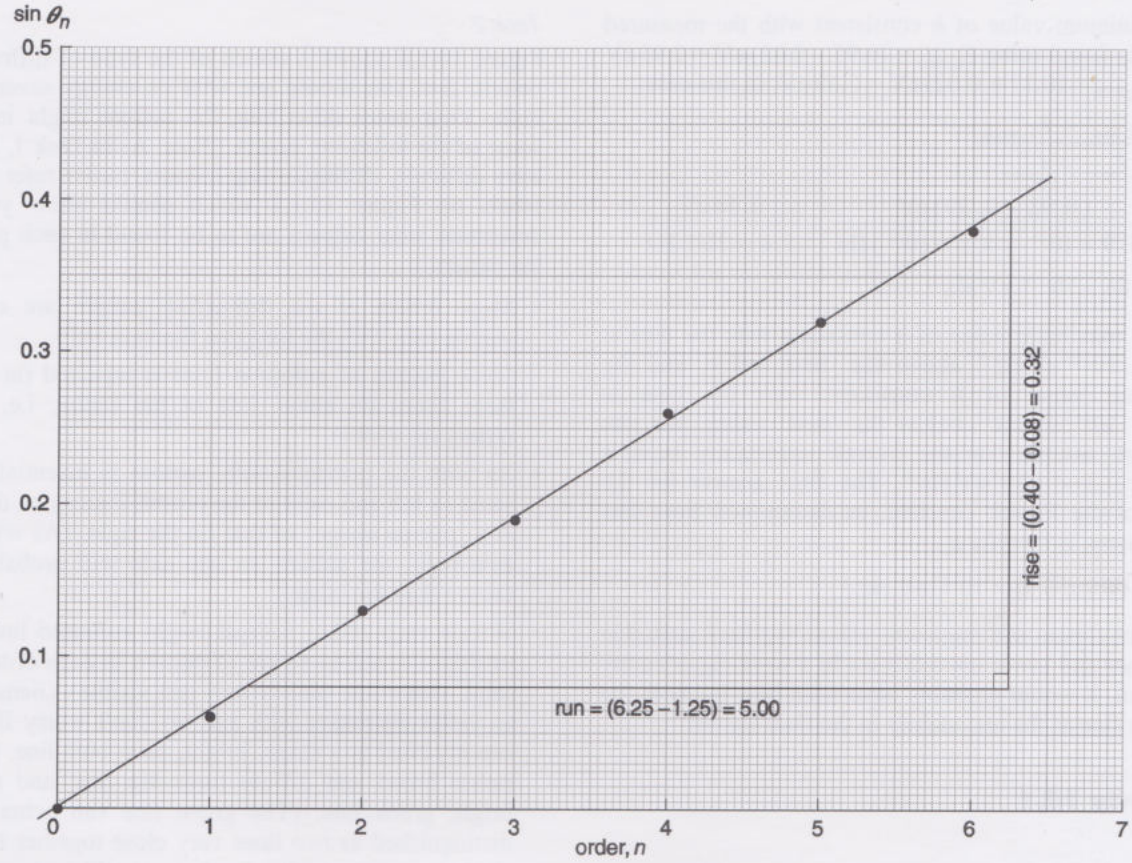


Figure 8.2.2 A graph of the data listed in Table 8.2.2, with a best-fit straight line drawn through the points. The gradient is determined using the construction shown, which allows the 'rise' and 'run' of the graph to be measured.

Activity 9.1

Task 1

For the blue line, the stopping voltages measured were: 0.96 V, 0.94 V, 0.98 V, 0.94 V, 0.95 V and 0.92 V. The mean stopping voltage for photoelectrons liberated by the blue light is therefore

$$\left(\frac{0.96 + 0.94 + 0.98 + 0.94 + 0.95 + 0.92}{6}\right) \text{V}$$

$$= \left(\frac{5.69}{6}\right) \text{V} = 0.95\,\text{V} \quad \text{(to two sig figs)}$$

The spread of these values is from 0.03 V above the mean to 0.03 V below it. Two-thirds of this spread is 0.02 V. So the final answer for the stopping voltage of the photoelectrons liberated by the photons of blue light may be quoted as (0.95 ± 0.02) V.

For the green line, the stopping voltages measured were: 0.36 V, 0.38 V, 0.37 V, 0.40 V, 0.34 V and 0.36 V. (Remember to disregard the measurement where the yellow line was used by mistake!) The mean stopping voltage for photoelectrons liberated by the green light is

$$\left(\frac{0.36 + 0.38 + 0.37 + 0.40 + 0.34 + 0.36}{6}\right) \text{V}$$

$$= \left(\frac{2.21}{6}\right) \text{V} = 0.37\,\text{V} \quad \text{(to two sig figs)}$$

The spread of these values is also from 0.03 V above the mean to 0.03 V below it, and two-thirds of this spread is once again 0.02 V. So the final answer for the stopping voltage of the photoelectrons liberated by the photons of green light may be quoted as (0.37 ± 0.02) V.

Task 2

The value for the Planck constant, as determined from these measurements is therefore:

$$h = \frac{E_{\text{k,blue}} - E_{\text{k,green}}}{f_{\text{blue}} - f_{\text{green}}}$$

$$= \frac{(0.95 - 0.37)\,\text{eV}}{(6.9 \times 10^{14} - 5.5 \times 10^{14})\,\text{Hz}} = \frac{0.58\,\text{eV}}{1.4 \times 10^{14}\ \text{Hz}}$$

$$= 4.14 \times 10^{-15}\ \text{eV Hz}^{-1}$$

It makes sense to retain the answer to three significant figures at this stage, as we have not yet determined the uncertainty in the calculated value.

Task 3

The maximum value of h consistent with the measured values is found using $E_{\text{k,blue}} = (0.95 + 0.02)$ eV = 0.97 eV and $E_{\text{k,green}} = (0.37 - 0.02)$ eV = 0.35 eV. In this case:

$$h = \frac{E_{\text{k,blue}} - E_{\text{k,green}}}{f_{\text{blue}} - f_{\text{green}}}$$

$$= \frac{(0.97 - 0.35)\,\text{eV}}{(6.9 \times 10^{14} - 5.5 \times 10^{14})\,\text{Hz}} = \frac{0.62\,\text{eV}}{1.4 \times 10^{14}\ \text{Hz}}$$

$$= 4.43 \times 10^{-15}\ \text{eV Hz}^{-1}$$

The minimum value of h consistent with the measured values is found using $E_{k,blue} = (0.95 - 0.02)\,eV = 0.93\,eV$ and $E_{k,green} = (0.37 + 0.02)\,eV = 0.39\,eV$. In this case:

$$h = \frac{E_{k,blue} - E_{k,green}}{f_{blue} - f_{green}}$$

$$= \frac{(0.93 - 0.39)\,eV}{(6.9 \times 10^{14} - 5.5 \times 10^{14})\,Hz} = \frac{0.54\,eV}{1.4 \times 10^{14}\,Hz}$$

$$= 3.86 \times 10^{-15}\ eV\,Hz^{-1}$$

So, the maximum value of h consistent with the data is $0.29 \times 10^{-15}\,eV\,Hz^{-1}$ above the 'best' value, and the minimum value of h consistent with the data is $0.28 \times 10^{-15}\,eV\,Hz^{-1}$ below the 'best' value. We can therefore assume that the overall uncertainty in h is about $\pm 0.3 \times 10^{-15}\,eV\,Hz^{-1}$. The final answer for the value of the Planck constant, as determined from this experiment, is therefore:

$$h = (4.1 \pm 0.3) \times 10^{-15}\,eV\,Hz^{-1}$$

If the maximum and minimum values had been such that the upper and lower uncertainties in h were significantly different, it would probably have been best to quote the larger value as the uncertainty in the final answer.

Activity 10.1

Task 1

Figure 10.1.7 shows a sketch of the type of diffraction pattern that you should see produced by a tungsten filament light bulb. Your notes describing the diffraction pattern might include some of the following points. (*Note*: If you have difficulty distinguishing colours, please refer to the labels on Figure 10.1.7 which should allow you to determine what colours are found in each part of the pattern.)

- Same rainbow pattern of colours is repeated (at least) twice on either side of centre. Pattern becomes fainter in the outer regions.
- Pattern is essentially the same on left and right-hand side of the centre, but pattern to the left is a 'mirror image' of that to the right. (One side will probably appear somewhat fainter than the other.)
- Each spectrum (i.e. each order) has violet nearest to the centre, and passes through blue, green, yellow, orange and red in sequence away from the centre.
- Spread (i.e width) of the spectrum is greater in second order than in the first order.
- Zero order of the diffraction pattern (at the position of the slit in the card) appears as a line of white light.

Now return to Task 2 in the notes on this activity.

Task 2

Figure 10.1.8 shows a sketch of the type of diffraction pattern that you should see with an energy saver light bulb. Your notes describing the pattern might include some of the following points. (*Note*: As in Task 1, if you have difficulty distinguishing colours, please refer to the labels on Figure 10.1.8 which should allow you to determine what colours are to be found in each part of the pattern.)

- More orders of the diffraction pattern are clearly visible than with the tungsten filament bulb.
- Same pattern of coloured lines is repeated (at least) three times on either side of the centre, i.e. three orders are visible.
- As with the previous bulb, pattern is essentially the same to left and right of the centre. Pattern on the left is a 'mirror image' of that on the right. (As with the first bulb, the pattern on one side will probably be fainter than the other.)
- Within each order, several bright coloured lines are visible. Closest to centre of pattern in each order is a faint, violet line (this is only just visible). (Sensitivity to violet decreases with age, so don't worry if can't see it!) Next is a sharp, bright, deep blue line, then a rather broad and diffuse turquoise line, and then a bright green line. (The green line can actually be distinguished as *two* lines very close together if your slit is narrow enough.) Further out still is a series of fainter (blurred) orange lines followed by a sharp, bright red line. Beyond the bright red line are several fainter red lines (which blur together as they fade away).
- Spread of the spectrum increases progressively in moving from the first order to the second and third orders. (In fact the red line of the second order of the pattern is very close to the blue line from the third order of the diffraction pattern. If it is possible for you to just glimpse the fourth order series of lines at the extremities of vision, you will notice that the orange lines of the third order actually overlay the blue line from the fourth order.)
- Zero order of the diffraction pattern (at the position of the slit in the card) appears as a line of white light.

Now return to the notes on this activity and try Questions 10.1.1 and 10.1.2.

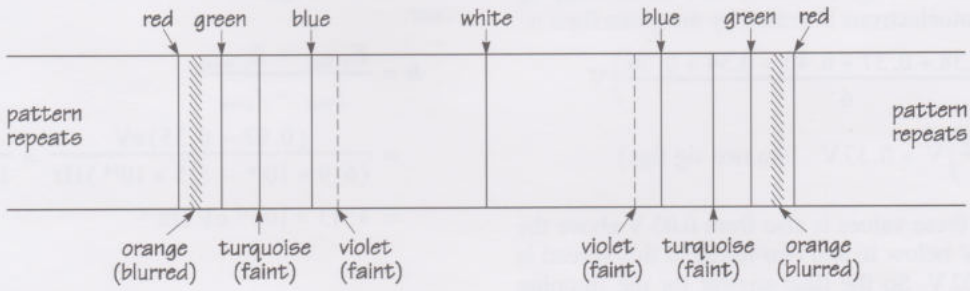


Figure 10.1.7 Sketch of the view through the diffraction grating showing the diffraction pattern produced by a tungsten filament light bulb.

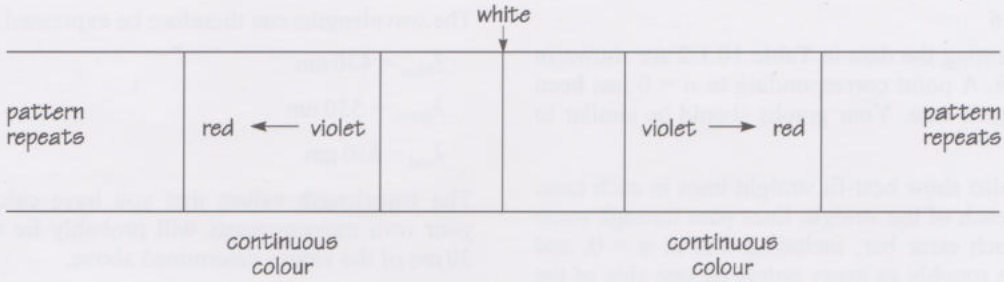


Figure 10.1.8 Sketch of the view through the diffraction grating showing the diffraction pattern produced by an energy saver light bulb.

Question 10.1.1 (a) Clearly the spectra of both the tungsten filament light bulb and the energy saver light bulb differ greatly from the spectra of the lasers that you saw in the DVD-video in Activity 8.1. A laser produces light of essentially a *single* colour — it's like having a single spectral line. So the diffraction pattern of laser light contains just a single point or line in each order of the diffraction pattern. The two light bulbs, on the other hand, each produce white light — a mixture of colours — and the diffraction grating allows you to see just what that mix of colours is.

(b) The tungsten filament bulb produces a *continuous spectrum* — the spectrum contains light of *all* colours, and so all wavelengths or frequencies within the visible region of the electromagnetic spectrum are present. The energy saver bulb on the other hand produces a *line spectrum* — the spectrum contains light only of discrete colours, and these appear as bright lines in the spectrum. The discrete colours correspond to specific wavelengths and frequencies within the visible part of the electromagnetic spectrum.

Question 10.1.2 In Section 7, the continuous spectral distribution of a tungsten filament was discussed, and the peak of its intensity was shown to be in the infrared part of the spectrum. All the radiation which is emitted outside the visible part of the spectrum is 'wasted', since it doesn't help to illuminate things for our eyes to see. Typically, 60 J of electrical energy per second (60 W) is supplied to such a bulb, but only a small fraction of this energy appears as light. All the infrared radiation merely heats up the surroundings of the bulb, as you will have noticed.

By contrast, an energy saver bulb emits its radiation in a series of spectral lines, most of which are in the visible part of the spectrum. Very little energy is 'wasted' by providing emission elsewhere in the spectrum. As a result, much less electrical energy need be supplied to such a bulb (typically only 12 J of electrical energy per second) in order to get the same intensity in the visible part of the spectrum as with a 60 W conventional bulb. There is very little infrared radiation from such bulbs, so they don't become so hot.

Now return to the notes on this activity.

Tasks 3 and 4

Some typical results are listed in Table 10.1.2 (overleaf). Note, these angles should be the same whether measured in the left or right orders of the diffraction pattern. Values for the angles in the fourth order are also shown, in case you were able to measure any lines in this order. The values that you measured will probably be within a couple of degrees of those given in Table 10.1.2.

Table 10.1.2 A completed version of Table 10.1.1. Values of θ_n and $\sin\theta_n$ for four orders for the blue, green and red spectral lines.

Order, n	θ_n/degrees	Uncertainty in θ_n/degrees	$\sin\theta_n$	Uncertainty in $\sin\theta_n$
Blue spectral line				
1	7.5	±1.0	0.13	±0.02
2	15.0	±1.0	0.26	±0.02
3	23.0	±1.0	0.39	±0.02
4	31.5	±1.0	0.52	±0.02
Green spectral line				
1	9.5	±1.0	0.17	±0.02
2	19.0	±1.0	0.33	±0.02
3	29.5	±1.0	0.49	±0.02
4	41.0	±1.0	0.66	±0.02
Red spectral line				
1	11.0	±1.0	0.19	±0.02
2	22.0	±1.0	0.37	±0.02
3	34.0	±1.0	0.56	±0.02
4	48.5	±1.0	0.75	±0.02

Tasks 5 and 6

Graphs illustrating the data in Table 10.1.2 are shown in Figure 10.1.9. A point corresponding to $n = 0$ has been included in each case. Your graphs should be similar to these.

The graphs also show best-fit straight lines in each case. Notice how each of the straight lines pass through some portion of each error bar, including that at $n = 0$, and that there are roughly as many points on one side of the line as on the other.

Task 7

The gradients of each of the three graphs illustrated in Figure 10.1.9 are calculated as the 'rise' in value up the vertical axis divided by the 'run' in value along the horizontal axis. The results are:

$$\text{blue line: gradient} = \frac{0.495}{3.82} = 0.130$$

$$\text{green line: gradient} = \frac{0.595}{3.60} = 0.165$$

$$\text{red line: gradient} = \frac{0.705}{3.76} = 0.188$$

Since neither $\sin\theta_n$ nor n have any units associated with them, the gradient has no unit either.

The gradients of your graphs will probably be within about 0.01 or so of the numbers here. In each case, the gradient is equal to the wavelength of the spectral line divided by the line spacing of the grating. Hence the wavelengths of the three spectral lines are:

blue line: $\lambda = d \times \text{gradient} = (3.33 \times 10^{-6}\,\text{m}) \times 0.130$
$= 4.33 \times 10^{-7}\,\text{m} = 433\,\text{nm}$

green line: $\lambda = d \times \text{gradient} = (3.33 \times 10^{-6}\,\text{m}) \times 0.165$
$= 5.49 \times 10^{-7}\,\text{m} = 549\,\text{nm}$

red line: $\lambda = d \times \text{gradient} = (3.33 \times 10^{-6}\,\text{m}) \times 0.188$
$= 6.26 \times 10^{-7}\,\text{m} = 626\,\text{nm}$

Clearly you could draw a range of lines through each set of points, each of which passed through most of the error bars, but each of which produced a slightly different value for the gradient. Each of these gradients in turn would result in a slightly different value for the wavelength of the spectral line in question. For instance, for the blue spectral line, gradients in the range from about 0.125 to 0.140 are all feasible with the data shown in Figure 10.1.9. This in turn leads to wavelength values between about 415 nm and 465 nm — that's from about 20 nm below to about 30 nm above the 'best' value calculated above. (Given more time, you could determine upper and lower limits to the gradients for each of your data sets, and so calculate upper and lower limits for the individual wavelengths. We don't expect you to do this here, however.) Bearing in mind the limitations discussed above, it would be unwise to quote the calculated wavelengths to more than two significant figures, since this would imply that there is confidence in the value to an accuracy of a few nanometres. Instead, quoting the wavelengths to only two significant figures implies that the wavelengths are accurate to a few tens of nanometres.

The wavelengths can therefore be expressed as:

$\lambda_{\text{blue}} = 430\,\text{nm}$

$\lambda_{\text{green}} = 550\,\text{nm}$

$\lambda_{\text{red}} = 630\,\text{nm}$

The wavelength values that you have calculated from your own measurements will probably lie within about 30 nm of the values determined above.

Task 8

Rearranging Equation 8.2 to make f the subject gives $f = \frac{c}{\lambda}$. So, for the three lines whose wavelengths were measured in Task 7, the frequencies are as follows:

$$\text{blue line: } f = \frac{3.0 \times 10^{8}\,\text{m s}^{-1}}{430 \times 10^{-9}\,\text{m}} = 7.0 \times 10^{14}\,\text{Hz}$$

$$\text{green line: } f = \frac{3.0 \times 10^{8}\,\text{m s}^{-1}}{550 \times 10^{-9}\,\text{m}} = 5.5 \times 10^{14}\,\text{Hz}$$

$$\text{red line: } f = \frac{3.0 \times 10^{8}\,\text{m s}^{-1}}{630 \times 10^{-9}\,\text{m}} = 4.8 \times 10^{14}\,\text{Hz}$$

Since the calculated wavelengths are only accurate to a few tens of nanometres (and quoted to two significant figures), the frequencies too should only be quoted to a similar level of accuracy. Your own values should reflect this level of uncertainty.

Task 9

Equation 9.1 states that the photon energy corresponding to a particular frequency of light is given by $E_{\text{ph}} = hf$ where h is the Planck constant and has a value of $4.1 \propto 10^{-15}\,\text{eV Hz}^{-1}$. So, for the three spectral lines whose frequencies were calculated in Task 8, the corresponding photon energies are:

blue line: $E_{\text{ph}} = (4.1 \times 10^{-15}\,\text{eV Hz}^{-1}) \times (7.0 \times 10^{14}\,\text{Hz})$
$= 2.9\,\text{eV}$

green line: $E_{\text{ph}} = (4.1 \times 10^{-15}\,\text{eV Hz}^{-1}) \times (5.5 \times 10^{14}\,\text{Hz})$
$= 2.3\,\text{eV}$

red line: $E_{\text{ph}} = (4.1 \times 10^{-15}\,\text{eV Hz}^{-1}) \times (4.8 \times 10^{14}\,\text{Hz})$
$= 2.0\,\text{eV}$

As above, a final quoted accuracy for the photon energies of two significant figures reflects the uncertainties in the procedure you have carried out. If you were to perform the experiment again, you would probably arrive at final answers that were within about 0.1 eV of those you have just determined.

Return to the notes on this activity and read 'Final remarks'

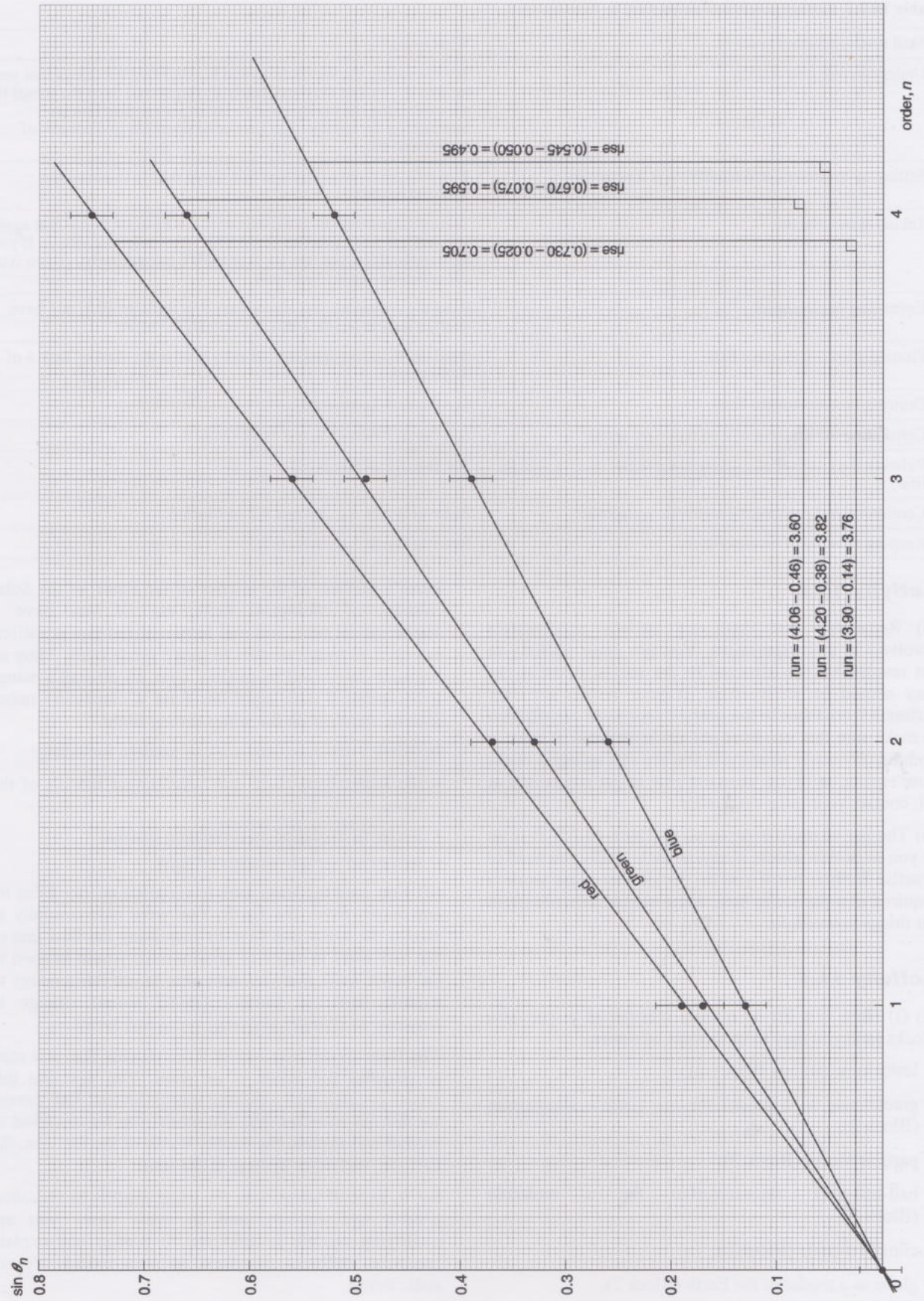


Figure 10.1.9 Graphs showing sin θ_n against n for the blue, green and red spectral lines, using the data listed in Table 10.1.2.

Table 10.2.2 Further practice of skills used in Activity 10.1.

Skill needing further practice	What to do
Understanding instructions	Try re-reading the instructions and highlighting the things that you have to do, so that they are clearly distinguished from the things that are explaining the background to the experiment or that are interpreting the results. Pay particular attention to diagrams of equipment, etc.
Setting up apparatus, and modifying it if necessary	You will get more practice at this if you decide to attend the SXR103 residential school.
Taking measurements	Taking measurements in experiments can be quite fiddly, but again you will get more practice at the SXR103 residential school. If you have difficulties, you can try to modify the experiment, or you could ask someone else to assist you.
Estimating uncertainties	Read the comments just above Task 3 in Activity 10.1, and have another look at Block 2 Box 2.1 and *SGSG* MH6.
Plotting graphs with error bars	Read again the explanations of error bars at the start of Task 5 of Activity 10.1.
Drawing best-fit straight lines	See Block 3 Section 12.
Calculating the gradient of a straight-line graph	See Block 3 Box 10.1 and *SGSG* MH10.
Relating the gradient of a graph to the equation of a straight line	See Box 8.3 of this block.
Combining and rearranging algebraic equations	Refer to Boxes 3.2, 3.3 and 4.2 in Block 5.
Keeping a record of an experiment	Refer to Block 5 Activity 6.2.

Activity 10.2

(a) Remember that there are various uncertainties involved in this experiment. You are quite unlikely to get results that are identical to the standard results but they should be fairly close. If your results are very different from those in the notes, check your calculations to make sure that you have not made an error. If there is nothing obviously wrong and you are still unhappy about your results, or if you were not able to get any results at all, contact your tutor-counsellor.

(b) The list of skills is repeated in Table 10.2.2. It is up to you to decide which, if any, of these skills you need to practise further, but if you do decide that more work is required in a particular area, some suggestions are given for things you can do.

Activity 11.1

(a) (i) Here is a list of models introduced in previous blocks (and you may have thought of others):

leaky tank analogy (Block 2);

greenhouse as a model for the Earth's atmosphere (Block 2);

particle model (Block 2);

ball-and-stick representation for a molecule (Block 2);

climate models (Block 2);

globe as a model of the Earth (Block 2);

paper cut-outs as a model for the Earth's tectonic plates (Block 3).

Most of these are analogies, used to exploit certain similarities of function, even if the model and the thing being modelled are superficially very different.

In a sense, many of the diagrams you have worked with are themselves models, e.g. drawings of the plates on the Earth's surface, of the interior of the Earth, of the Solar System, of biological cells, etc. If you have a mathematical bent, you will have realized that equations are used in many models to make predictions. Thus an engineer interested in airflow over an aircraft's wings investigates it with equations (and a computer) rather than by standing on the wings during flight.

In Block 7 you have met various models, including:

- the Rutherford, Bohr and Schrödinger models of the atom;
- nucleons modelled as containing quarks;
- wave and particle models of light.

(ii) You used the leaky tank to *visualize* energy gains to, and losses from, the Earth. You were able mentally to *modify* the leaky tank (e.g. by increasing the flow rate or the leak rate) in order to *predict* what would happen to the water level, and you were able to use this analogy to explain how the Earth's GMST would change in response to changes in energy gains and losses.

The Bohr model was one of three models that you used to *visualize* the inside of an atom. You saw that this model *predicts* and *explains* energy levels. And though we did not mention this, the model can be modified to predict and explain the energy levels of the He^+ ion, the Li^{2+} ion, and other hydrogen-like ions.

So, in general terms, you are using models to *visualize*, *predict* and *explain*, and in many cases you are modifying models to help you to predict and explain somewhat different situations, so most models are not static things.

(iii) All of the models represent the real situation to a certain extent, but that does not mean that they *are* the real situation. You are probably quite happy to accept this when talking about a model which is obviously not the same as the thing you are using it to represent (e.g. the atmosphere is not really a greenhouse), but it is easy to fall into the trap of thinking that the inside of an atom really looks like the Rutherford, Bohr or Schrödinger

model, or that light really is a wave or a particle. In a sense this is a limitation — models represent reality without being reality. However, models are also an extremely powerful scientific tool. They help us to visualize things which we can't see in the conventional way, and they help us to understand the workings of the scientific world around us. Light is not really either a wave or a particle (at least, not in the sense in which we commonly think of waves and particles), but it is extremely useful to be able to think of light as a wave when it propagates through space and as a particle when it interacts with matter. And when we're using models in the knowledge that they are only a representation of the real situation, our models don't have to be particularly sophisticated. As noted in the comments on Activity 2.1, the Bohr model has various shortcomings, but it is reasonably adequate as an explanation of how atoms combine (in chemistry) and hence as an explanation of the world which we will be putting together again in the later blocks of *Discovering Science.*

(iv) Once you have accepted that models are useful, but do not have to be realistic, it becomes helpful to devise models for yourself as part of your own learning process. As the course progresses, we will introduce a variety of new models, and we encourage you to think of others for yourself. You will probably discover that models that you have thought of for yourself are even more useful than those that we have suggested.

There are no comments on part (b).

Further reading

Close, Frank (1983) *The Cosmic Onion*, Heinemann Educational Books. This book gives a largely historical account of how 'quarks and the nature of the Universe' (the book's subtitle) were discovered. It also covers much of the material in this block, as it progresses through the various layers of the cosmic onion from atoms, to nuclei, to nucleons, to quarks.

Davies, P. C. W. and Brown, J. R. (eds) (1986) *The Ghost in the Atom*, Cambridge University Press. This book presents an entirely non-mathematical discussion of quantum theory. The first half is a summary of quantum ideas, and the second half is a series of interviews with eight leading quantum physicists, each of whom tackles a different aspect of the subject. As well as covering the puzzles and paradoxes thrown up by quantum theory, this book also tries to make sense of its strange philosophical implications.

Gamow, George (1993) *Mr Tompkins in Paperback*, Cambridge University Press. This book covers many aspects of quantum theory and relativity, but the chapters of most relevance to this block are those in which Mr Tompkins travels to a world in which the Planck constant has a value hugely larger than in our own Universe. The quantum effects thus become much more noticeable in everyday situations.

Objectives for Block 7

The objectives state what you should understand and what you should be able to do after studying the block.

The numbers of questions and activities that test each objective are given in italics. In the margin next to some objectives are references to *The Sciences Good Study Guide (SGSG)*, giving the chapter: section number or Maths Help (MH) number, or to DVD material, where you can find additional support.

Science content

1 Explain the meaning of, and use correctly, all the terms printed in **bold** in the text.

2 Recall the constituents of atoms and of nuclei, and recall that leptons and quarks are fundamental particles. (*Questions 3.2–3.4, 3.7, 3.8, 4.1–4.3 and 5.1–5.6; Activities 3.1, 4.1, 5.1 and 6.1*)

3 Use the concept of quanta to explain emission and absorption of light and other electromagnetic radiation, and relate this to the spectra of atoms, the energy-level diagram of atoms and the photons emitted and absorbed when transitions between energy levels occur. (*Questions 1.1, 2.1–2.12, 3.1–3.3; Activities 4.1 and 10.1*)

4 Recall that any system of particles that are bound together is a quantum system and therefore has states of definite energy (energy levels) between which quantum jumps (transitions) occur. (*Questions 2.5–2.12, 3.1–3.3, 3.6, 4.1 and 4.2; Activities 4.1 and 5.1*)

5 Describe key features of the Rutherford, Bohr and Schrödinger models of the hydrogen atom, including why the first two fail to describe the quantum world correctly, whereas the Schrödinger model predicts the intrinsic uncertainty of the position and motion of an atom's constituents and represents this by an electron cloud. (*Questions 3.2–3.4, 3.7, 3.8; Activities 2.1 and 4.1*)

6 Use two quantum numbers to label quantum states of hydrogen atoms and to describe the electron configuration of atoms with more than one electron, and appreciate the role of the Pauli exclusion principle in determining these electron configurations. (*Questions 3.5, 3.6 and 4.3; Activities 3.1 and 4.1*)

7 Recall that the Heisenberg uncertainty principle imposes limitations on the accuracy with which certain quantities can be simultaneously known. (*Question 3.9*)

8 Compare and contrast the energy levels, spectra and electron probability clouds of atoms, or ions, of hydrogen, helium and lithium. (*Questions 4.1 and 4.2; Activity 4.1*)

9 Interpret the pattern of stable and unstable nuclei represented by the N–Z chart and the valley of the nuclides, and use values of nuclear masses or mass excesses to determine which decays occur. (*Activity 5.1*)

10 Write isotope equations for the nuclear transformations that occur in the processes of α-decay, β^--decay, β^+-decay, γ-decay and electron capture, and in nuclear fission. (*Questions 5.1–5.6; Activities 5.1 and 6.1*)

11 State which combinations of quarks occur in hadrons, and explain simple reactions involving quarks in terms of strong and weak interactions. (*Questions 6.1–6.4; Activity 6.1*)

12 Describe how light (and other electromagnetic radiation) propagates as a wave, but interacts with matter as a stream of particles, and how electrons (and other things usually thought of as particles) also behave in this dual manner. (*Questions 8.4, 8.12–8.15, 9.1–9.6 and 10.1; Activity 10.1)*

13 Describe a wave in terms of its wavelength, frequency (or period) and propagation speed, and calculate these quantities given knowledge of several others. (*Questions 8.1–8.4, 8.13–8.15; Activities 8.1, 8.2, 9.1 and 10.1*)

14 Recall that diffraction is a phenomenon common to all types of wave, and recall the conditions under which it occurs. (*Questions 8.10–8.12 and 10.1; Activities 8.1, 8.2 and 10.1*)

15 Relate different regions of the electromagnetic spectrum to the wavelength and frequency of radiation and the energy of photons. (*Questions 2.3, 8.13–8.15, 9.4 and 9.6*)

16 Explain how the photoelectric effect provides evidence for the particle-like interaction of light with matter and how it can be understood in terms of the conservation of energy. (*Questions 9.1–9.6; Activity 9.1*)

17 Recall the meaning of the following equations, and use them correctly:

$E_{ph} = \Delta E_{atom}$	(*Questions 2.5–2.11, 3.1 and 3.2; Activity 10.1*)
$E_n = Z^2 \times \left(\frac{-13.60\ \text{eV}}{n^2}\right)$	(*Questions 2.9, 3.1, 3.2, 3.6, 4.1 and 4.2; Activity 4.1*)
$E = mc^2$	(*Question 5.2; Activities 5.1 and 6.1*)
$c = f\lambda$	(*Questions 8.3, 8.4 and 8.13–8.15; Activity 10.1*)
$\sin\theta_n = \frac{n\lambda}{d}$	(*Question 8.12; Activities 8.1, 8.2 and 10.1*)
$E_{ph} = hf$	(*Questions 9.1, 9.2 and 9.5; Activities 9.1 and 10.1*)
$E_{k,max} = E_{ph} - E_0$	(*Questions 9.3, 9.5 and 9.6; Activity 9.1*)

Science skills

SGSG 8: 1–3 18 Carry out an experiment, including designing and setting up the equipment from a general specification, planning the procedure to be used, making observations and measurements, recording data with estimates of uncertainties, analysing results, comparing results with published data, and stating a conclusion. (*Activities 9.1 and 10.1*)

SGSG MH10 19 Plot graphs of tabulated data, and include error bars where appropriate. (*Activities 8.2 and 10.1*)

SGSG MH10 20 Determine the gradient of a straight-line graph. (*Questions 8.7–8.9; Activities 8.2 and 10.1*)

21 Use models and analogies to aid understanding of scientific concepts and explain them to others. (*Activities 2.1, 3.2 and 11.1*)

Communicating science skills

SGSG 3 22 Produce, and interpret, graphs and diagrams that convey concepts and quantitative information. (*Questions 2.1, 2.2, 2.4, 2.7, 2.8, 2.11, 3.3, 3.7, 3.8, 7.1, 8.3 and 8.4; Activities 4.1 and 5.1*)

SGSG MH9 23 Use symbols and equations to communicate scientific ideas. (*Most questions and activities involving calculations*)

SGSG 4: 5 24 Present written answers to numerical questions in an appropriate way. (*Most questions and activities involving calculations*)

SGSG 9: 5.4 25 Produce an appropriately structured written account of an experiment. (*Activity 10.1*)

Mathematical skills

26 Relate the concepts of sine, cosine and tangent to the sides and angles of a right-angled triangle, and carry out calculations on a calculator using these functions. (*Questions 8.5 and 8.6; Activities 8.2 and 10.1*)

27 Relate the equation of a straight line to a graph. (*Questions 8.7–8.9; Activities 8.2 and 10.1*)

28 Rearrange and combine algebraic equations in order to calculate a desired quantity from other known quantities. (*Questions 8.4, 8.14, 8.15 and 9.3–9.6; Activities 8.1, 8.2, 9.1 and 10.1*) — *SGSG* MH9; Block 3 DVD 'Algebraic manipulation'

29 State the SI units of wavelength, frequency and period (of a wave), and use these units correctly in calculations. (*Questions 8.2, 8.3, 8.12–15, 9.4 and 9.5; Activities 8.1, 8.2, 9.1 and 10.1*) — *SGSG* 5: 4

30 Use the electronvolt (eV) as a unit of energy and the electronvolt/c^2 (eV/c^2) as a unit of mass. (*Many questions and activities)*

31 Analyse rates of exponential decay using the concept of half-life. (*Activity 5.1*)

Effective learning skills

32 Review and reflect on various study and learning techniques used, particularly those associated with scientific models, and modify use of these techniques in the light of experience. (*Activities 2.1, 3.2 and 11.1*) — *SGSG* 1: 4

33 Review and reflect on practical skills. (*Activity 10.2*)

34 Use a computer database in order to find information. (*Activities 5.1 and 6.1*)

Appendix What to do if you are short of time

This brief guide to the activities in Block 7 should help you to decide for yourself whether you need to do a particular activity. Remember, though, that if you have the time you should aim to do *all* the activities in order to obtain the full benefit from your study.

The five numbered columns offer advice about each activity as follows:

1 essential that you do this activity at the particular point in Book 7 where it appears;

2 important, but there is more flexibility about when you do this activity, although you should try to complete it before moving onto the next section of Book 7;

3 may not be essential if you have some background already in the topic or skill, or have found earlier, similar activities straightforward;

4 could be left until later on, or dropped altogether if you are really short of time;

5 forms a useful tool for revision before you move on to higher level chemistry or physics courses.

The last column on the right contains additional advice about some of the activities.

Block 7 activities

Activity	Category					Comments
	1	2	3	4	5	
2.1				✓		Useful for reflection
3.1					✓	
3.2				✓		Useful for reflection
4.1	✓					Essential for progressing through Section 4
5.1	✓					Essential for understanding Section 5
6.1	✓					Essential for understanding Section 6
8.1		✓				Best studied early in Section 8
8.2		✓				Best studied early in Section 8
9.1		✓				Needs to be studied before the end of Section 9
10.1		✓				Needs to be studied before the end of Section 10
10.2			✓			Useful for reflection
11.1				✓		Useful for reflection